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An experimental assessment of combustion, emission, and performance behavior of a diesel engine fueled with newly developed biofuel blend of two distinct waste cooking oils and metallic nano-particle (Al_2O_3)

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Engine performance;
Combustion;
Emission characteristics.

Abstract. In the current experimental study, biofuel was extracted from two distinct waste cooking oils of palm and sunflower through a transesterification process. To this end, a suitable blend B20 (WCPME 10% + WCSME 10% + Diesel 80%) was prepared by mixing diesel with the biofuel. Then, an ultrasonicator was utilized to mix Al_2O_3 in B20 at distinct proportions of 25, 50, and 100 ppm, respectively, and to develop new ternary blends of B20 + $25Al_2O_3$, B20 + $50Al_2O_3$, and B20 + $100Al_2O_3$. The experiment test was conducted on a Common Rail Direct Injection (CRDI) engine fueled by diesel, B20, B20 + $25Al_2O_3$, B20 + $50Al_2O_3$, and B20 + $100Al_2O_3$ samples at a steady speed of 1500 rpm under different engine loads to evaluate the performance, combustion, and emission characteristics of the mentioned engine. The test results revealed that Brake Thermal Efficiency (BTE) was extensively improved by 13.53% and Specific Fuel Consumption (SFC) was reduced by 20.93% for B20 + $100Al_2O_3$ rather than B20 at the full load. The emission characteristics such as CO and HC were altogether reduced by mixing the nanoparticles in the correlation of B20 and D100; however, a slight increment was observed in NOx emissions, compared to B20 and D100 cases. Higher peak points in both CPmax and HRRmax reached B20 +$100Al_2O_3$ mainly due to the reduced ignition delay compared to those in B20 and D100.

1. Introduction

There are all-inclusive worries over rising oil costs, rapid depletion of fossil fuels, increased pollution, and ozone repercussions that threaten substance emanations. According to a recent estimation of the United States Agency for International Development (USAID), energy requirement is expected to increase above 50% in 2040 compared to that in 2018 [1,2]. Adaptation to worldwide changes demands considerable energy-saving and advancement of new options sustainable for this purpose. For this reason, researchers constantly seek an alternative renewable source of energy. In this regard, biofuels may be the best alternative sources of energy whose capabilities can be highlighted from the practical, political, and natural points of view. As far as their advantages are concerned, one refers to them as the elective fuels that can solve several problems including (1) the increased energy prices worldwide due to rapid depletion of conventional fuel; (2) the rising need for energy in industries, agriculture, and transport systems that are highly reliant on petroleum-based fuels; (3) the environmental repercussions of

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fossil fuel combustion; and (4) the security of national energy supply [3–8]. Biofuel is derived from several sources including vegetables, animal fats, algae oil, and microbial oil. It is a non-toxic, renewable, eco-friendly, biodegradable substance made of sulfur-free contents. Given that it contains some physio-chemical properties similar to those of diesel fuels, it is compatible to be used in diesel engines without modification [9]. Since biofuel is a highly viscous fuel, using straight vegetable oil in the diesel engines would cause several problems including poor atomization, advanced injection, injector chokes, and piston ring sticking [10]. In this regard, manifold techniques are employed to reduce the viscosity of biofuels including pyrolysis, distillation, micro-emulsion, reactive distillation, microwave technology, supercritical method, and transesterification [11].

Transesterification is a widely used method where alcohol is used with biofuel in the presence of an appropriate catalyst and heated to a range of 60–70°C to chemically break the heavy triglyceride molecules of raw biofuel into ethyl and methyl esters with glycerol as a by-product. The obtained mono-alcohol ester has viscosity one-third of that of the third biofuel. Figure 1 presents the mechanism of the transesterification process [11].

The biofuel used in diesel engines reduces harmful emissions such as CO, CO_2, and HC and slightly increases NO_X. Moreover, biofuel addition reduces Brake Thermal Efficiency (BTE) and increases Breake Specific Fuel Consumption (BSFC). In the experimental investigation of the four-stroke diesel engines fueled by WPOME and COME, engine emissions, i.e., CO, HC, and smoke opacity decreased by 14.29%, 9.52%, 86.89%, 72.68%, 67.65%, and 47.96%, respectively, in both types of oils. However, a slight increment in NO_X emissions was observed [12]. The molecular structure of biofuels is characterized by O_2 molecular double bonds that are shorter than single bonds, thus reducing compressibility and increasing bulk modulus, hence earlier injection time, reduced radiative heat transfer, higher unsaturation, and higher combustion flame temperature [13]. NO_X harmful emission is a serious problem to commercializing biofuels. Therefore, researchers are looking for an appropriate, reliable, and reasonable technology to reduce NO_X emissions. They found that some fuel additives containing antioxidants and nanoparticles could reduce NO_X emission. The incorporated antioxidant additives N, N′-diphenyl-1,4-phenylenediamine, and N-phenyl-1,4-phenylenediamine in soybean biodiesel were taken into account to study the emissions of diesel engines. According to the findings, CO and HC increased up to 14% and 16%, respectively, and NO_X and BTE were reduced by 0.8% and 0.8%, respectively [14]. Similarly, N, N-diphenyl-1,4-phenylenediamine was mixed with the Jatropha diesel mixture and consequently, 16% reduction in NO_X and more reduction in CO and HC emissions were reported [15]. Antioxidants used as fuel additives reduced NO_X emissions and increased BSFC, HC, and CO emissions [16]. On the contrary, addition of nanoparticles to the biodiesel improved its physicochemical properties. The reduced viscosity of the resultant fuel could provide better atomization and dispersion, and mixing the fuel resulted in the improvement of the combustion characteristics. Consequently, improved combustion and physiochemical properties of the fuel would enhance the engine performance (BTE, BSFC). The high surface-to-volume ratio of nanoparticles provided additional reaction surfaces in the air-fuel mixture, hence accelerating combustion, rapid flame propagation, proper fuel dispersion, early absorption of latent heat of vaporization, rapid heat transfer in the air-fuel, and early fracture of thermal hydrogen compounds [17]. The impact of carbon-covered Al nanoparticle blends in the palm biodiesel on the engine performance and outflow qualities of four-cylinder in-line Common Rail Direct Injection (CRDI) was also evaluated under a distinctive load condition. Carbon-covered nanoparticle blend biofuel fuel reduced BSFC, NOx, and CO by 10%, 12%, and 9%, respectively [18]. In the case of nanoparticle size, the increased CuO size improved the performance of both diesel engine and emission characteristics. The experiment was conducted for three types of a blend, namely BD100CuO20, BD100CuO10, and BD100. It can be concluded that CuO with a particle size of 20 nm increases BTE up to 0.9% over BD100 and 0.2% over BD100CuO10. Since the kinematic viscosity of BD100CuO20 is lower than those of BD100CuO10 and BD100, the droplet size of the fuel is reduced, thus

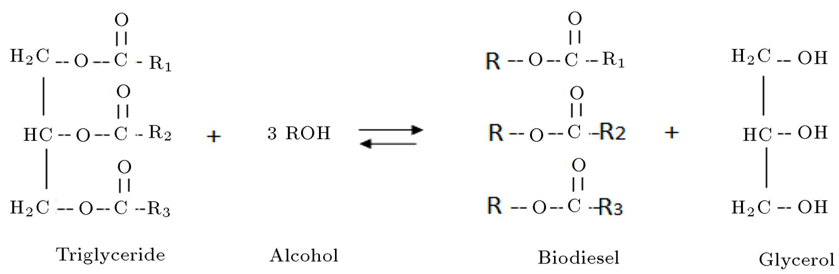

Figure 1. Transesterification process.

resulting in proper atomization, dispersion, mixing, combustion of the fuel, and consequently reduction in the BSFC and CO emissions. The discharged HC and NO_X in BD100CuO20 are smaller than those in BD100CuO10 and BD100, mainly because the expanded size of nanoparticle builds the contact between the fuel and air as well as lower HC outflows. Enlarged size accelerates the evaporation rate which leads to a reduction in the ignition delay. The lesser BSFC, CO, HC, smoke, and NO_X emissions as well as higher BTE of diesel engines support the addition of nanoparticles in the biodiesel [19]. The experiment was done on a four-stroke direct-injection air-cooled engine at a speed of 2000 rpm under different load conditions. Three types of blends (B30 + $50Al_2O_3$, B30 + 50 ZnO, and B30 + 50MgO) were used as fuels in C.I. engines in this study. According to the reports, the minimum BSFC for B30 - 50 MgO was 176 kg/kWh, and BTE for fuel blend B30 + 50MgO increased by 47% under the full load condition. Nanoparticle addition increased the calorific value of fuel, which in turn increased the brake power. Nanoparticles are the oxygenated catalysts used to improve combustion, which can reduce fuel consumption [20]. Further development of fuel characteristics can considerably enhance the volatility, turbulence ratio, and dispersion of the fuel in the combustion chamber. Improved thermo-chemical combustion characteristics can reduce the ignition delay, cylinder pressure, and heat transfer, hence reduction in the CO, NO_X, and HC emissions. Three types of nanoparticles namely CNT, titanium oxides, and Al_2O_3 at different nanoparticle sizes (25, 50, and 100 ppm) were mixed with B20 Jatropha biodiesel blend. The results from the tests revealed that the mixture of biodiesel with Al_2O_3 and J20Al100 could improve the BTE up to the highest amount of 6.5%, while jatropha biodiesel was mixed with CNT since J20C50 reduced CO and NO_X emissions by 35 and 52%, respectively [21]. Expansion of Al_2O_3 nanoparticles into the biodiesel mix JB20D would increase the heating value, hence an increase in the self-ignition temperature. The self-ignition temperature of the fuel is straightforwardly identified with a short ignition delay period as a result of which the engine power would be enhanced. In addition, the expansion of Al_2O_3 increases the oxygen content in charge and makes the ignition of air-fuel combination coming from legitimate burning happen inside the burning chamber. Al_2O_3 has higher thermal conductivity because of which the dissipation pace of fuel drops would be expanded, thus diminishing the ignition delay and enhancing the engine performance [22]. Researchers are still exploring metallic nanoparticles as a fuel mix to further develop engine combustion. The metallic nanoparticles, Al_2O_3, function as an ignition catalyst for hydrocarbons fuels [23]. According to the test results, J20Al100 at 75% of the engine load contains the most minimal BSFC in contrast with the diesel and other tried fuels [24–26]. This result was obtained from Tafel extrapolation strategy expansion of lower erosion rates of Al_2O_3 nanoparticles. According to the findings about the after-effects of the erosion test conducted based on cyclic potentiodynamic polarization strategy, the pitting consumption opposition was enhanced with the addition of Al_2O_3 nanoparticles. It was dependent upon Al_2O_3 application as nanoparticles in biodiesel. It is demonstrated that use of a fuel added substance might be suitable for the engine combustion chamber and its parts [27]. For engine investigation, there are various fundamentals to focus on the effect of nano-included substances associated with engine power. In this way, some experiment investigations were derived from the blends between nano-added substance and biodiesel and diesel fuel to foster the fuel properties and engine performance, similar to reduction of the engine emissions [28]. According to the related literature, Al_2O_3 is characterized by higher warm conductivity, corrosion resistance, and burning catalyst and oxygen benefactor. Higher thermal conductivity, ignition catalyst, and oxygen content further develop the heat release rate, the evaporation rate of fuel, air-fuel blending, air-fuel scattering, and effective burning which may further develop the combustion attributes. From various investigations of different nanoparticles, it was seen that Al_2O_3 added substance in biodiesel fuel further developed BSFC and BTE in contrast with other metallic nanoparticles. Corrosion resistivity can be considered to be safe for the engine combustion chamber and its parts. In the analysis, it was seen that mixing of Al_2O_3 and waste cooking biofuel further developed the heating value of fuel, which might improve BTE and BSFC and enhance the outflow attributes of diesel engine. To keep these factors in mind, Al_2O_3 is selected as the fuel added substance. According to the literature, given the mixture of metal oxide nanoparticles in biodiesel, the addition of nanoparticles improved the physical and chemical properties of the fuel as well as the engine performance, combustion, and emission characteristics of diesel engines. Nanoparticles appear in various forms. A expert is able to investigate what sort of nanoparticle is proper for particular kinds of biofuel. Dumping of waste cooing oil pollutes water which is a severe issue. It is the best strategy to utilize Waste Cooking Oil (WCO) as a supporting biofuel with edible, non-edible, and diesel oils. This experimental study investigates the utilization of Al_2O_3 nanoparticles as a fuel additive in a biofuel blend of two WCOs in a diesel engine. In this exploratory examination, biofuel blend of WCOs of palm and sunflower was utilized. From the literature research, it was found that the engine produced maximum engine performance, improved combustion characteristics, and decreased harmful emissions by

20% of biofuel blend in diesel fuel. These are the reasons why 20% of waste cooking biofuel concentration in this experiment study was selected for blend in diesel. This research aims to investigate the technical feasibility of blending with Al_2O_3 nanoparticles to form additives as an alternative fuel for direct injection to CRDI VCR diesel engine without requiring any changes to the existing engine. Mixture of nanoparticles and a biofuel blend of WCO discloses future expectations of researchers concerning renewable energy sources.

2. Materials and methods

2.1. Biofuel preparation process

WCO of palm and sunflower oils was collected from a number of hotels and restaurants in Noida (Uttar Pradesh). In the next step, food residuals were filtered from the WCO and then, their physiochemical properties were checked. It was found that their viscosity and density were moderately high. Transesterification process was undertaken to reduce the fuel viscosity. In this process, WCOs of different types were separately treated in a reaction flask under the following condition: molar ratio of 6:1, KOH of 1%w/w catalyst, temperature of 60°C–70°C , and RPM of 400. Followed by this process, the mixture was settled down for two hours. The glycerol was separated by the biofuel due to sedimentation. Figure 2 illustrates the separation of glycerol from the biofuel after the transesterification process. Next, the newly developed supporting biodiesel sample (B20) was prepared as a mixture of 20% waste cooking methyl ester (10% + WCPME + 10% WCSME) and 80% diesel. Table 1 lists each obtained WCO as well as the properties of the newly developed biofuel sample tested in the DTU labs. Anton paar SVM smart viscometer (given in Figure 3) was then used to measure the kinematic viscosity, dynamic viscosity, and density of developed fuel samples.

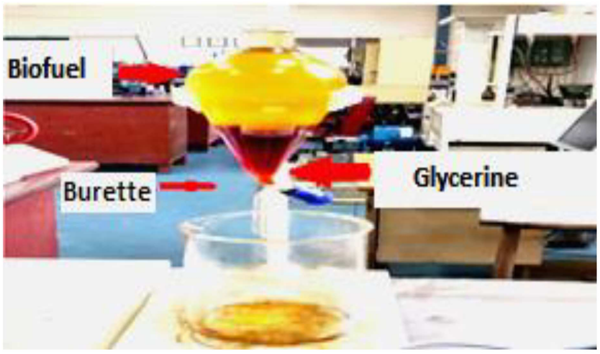

Figure 2. Biofuel separated from glycerol (DTU lab).

Figure 3. Anton paar SVM smart viscometer (DTU lab).

2.2. Nanoparticle testing by XRD and TEM

As shown in Figure 4, nanoparticle Al_2O_3 was selected for experimental investigation. Al_2O_3 was provided from nano research lab H-21, Gopalpur, Po-Assanboni, Jharkhand-832102. Table 2 shows the physiochemical properties of the utilized nanoparticle. The morphological characterization of Al_2O_3 was tested by Transmission Electron Microscopy (TEM) at nano research lab Gopalpur and X-Ray-beam Diffraction (XRD) at Delhi Technological University (DTU). In the current study, TEM is the preferred method to straightforward determination of the size distribution,

Table 1. Properties of diesel and modified fuel.

Oil	Density (kg/m^3)	Dynamic viscosity (mPa.s)	Kinematic viscosity (mm^2/s) at 40°C	High calorific value (kj/kg)	Acid no. (mg KOH/g oil)	Saponification value (mgKOH/g)	Flash point (°C)
D100	0.8107	1.8845	2.3244	42875	–	–	91.7
Unused palm oil	0.8965	32.777	36.562	38642	3.79	199.3	195
Used palm oil	0.9003	36.952	41.043	39847	28.12	246	260
Used palm biofuel (after trans)	0.8599	3.8322	4.4579	40509	0.344	180.4	> 100
Unused sunflower oil	0.950	28.252	31.217	38.8	0.1903	190.5	307
Used sunflower oil	0.9061	29.441	32.508	39.76	2.12	218	312
Used sunflower biofuel (after trans)	0.8677	3.7329	4.3019	40.02	0.396	168	> 100

Figure 4. Al_2O_3 nanoparticles.

Table 2. The physio-chemical properties of (Al_2O_3).

Form	Powder
Color	White
Order	Order less
Melting point	2072°C
Boiling range	2500–3000°C
True density	3.9 g/cm^3
Morphology	Spherical
Crystallographic structure	Rhombohedral
Molecular weight	121.96 g/mol
Molecular formula	Al_2O_3
Bulk density	1.5 g/cm^3
Purity	99.9%
SSA	120–140 m^2/g
Average particle size	10–20 nm

size, grain size, and morphology of the nanoparticle samples. The XRD is a research facility-based method that is normally used for crystalline materials, sample purity, morphology, and analysis of unit dimensions. Figures 5 and 6 depict the XRD and TEM images of Al_2O_3, respectively. The investigated material is a finely ground homogenized nanoparticle with normal bulk composition.

2.3. Preparation of nanoparticle biofuel blend sample

In this experimental study, Al_2O_3 was separately added to the supporting biodiesel B20 (WCPME 10%+ WCSME 10%+ Diesel 80%) at different ratios. Each nanoparticle was weighted to a mass fraction of 100 ppm. The nanoparticle was then added to 1 kg diesel fuel at different ratios of 25 mg, 50 mg, and 100 mg in that order. Subsequently, each sample fuel was dispersed by ultrasonicator at a frequency of 40 kHz and 300 W for 30 minutes. Ultrasonicator is a popular method for dispersing homogeneous

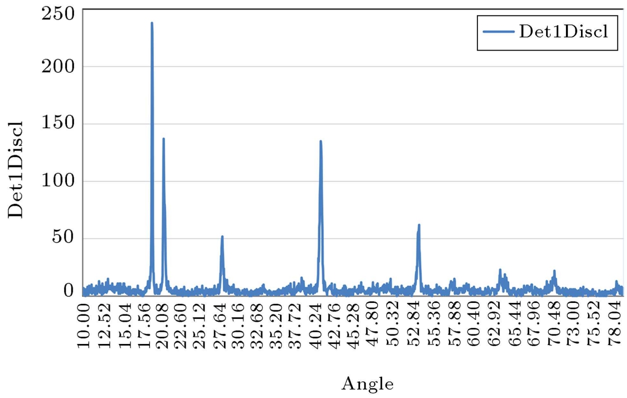

Figure 5. XRD analysis of Al_2O_3 nanoparticles.

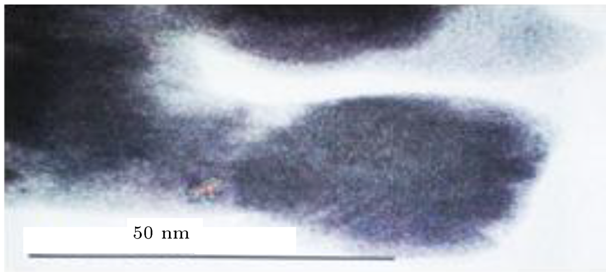

Figure 6. TEM analysis of Al_2O_3.

nanoparticles in biofuels. It also prevents the agglomeration of the nanoparticles using high pulsating frequency; otherwise, the nanoparticles are collectively clustered to shape a micro molecule, thus becoming residue. New nanoparticle fuel samples were developed as B20+25PPM(Al_2O_3), B20+50PPM(Al_2O_3), and B20+100PPM(Al_2O_3). The physio-chemical properties of the new samples are given in Table 3.

3. Experiment procedures

3.1. Experimental setup

In the present experimental study, Kirloskar AVI, four-stroke single-cylinder Variable Compression Ratio (VCR) diesel engine assisted by the CRDI system was utilized to conduct experimental tests at the DTU laboratory. More detailed specifications and block diagram of the diesel engine are shown in Table 4 and Figure 7. The engine was directly coupled to an eddy current dynamiter with the maximum power of 7.5 kW, which was used to load and unload the VCR diesel engine. The fuel consumption was estimated by a standard glass burettes two-way valve. A sharp edge orifice meter in the air box was broadly acknowledged and employed to measure air intake into the cylinder. A U-tube manometer was used to calculate the difference in the pressure of the different sides. The gas discharge from CI engines, including HC, CO, and NO_X, was estimated using AVL DIGAS444 exhaust gas analyzer. In this respect, IC engine soft

Table 3. New developed biofuel physio-chemical properties.

Oil	Dynamic viscosity (kg/m^3) at 40°C	Kinematic viscosity (mm^2/s) at 40°C	Density (kg/m^3)	High calorific value (kJ/kg)
WCME (50% WCPM + 50% WCSM)	3.7978	4.3984	0.8635	39876
Supporting biodiesel B20 (WCPM10%+ WCSM10%+ Diesel80%)	2.0149	2.4696	0.8159	40365
B20+25 PPM (Al_2O_3)	2.1800	2.6574	0.8203	40503
B20+ 50 PPM (Al_2O_3)	2.2004	2.6876	0.8303	40752
B20+100 PPM (Al_2O_3)	2.3665	2.8765	0.8777	41202

Table 4. Engine specification.

Engine model	**CRDI VCR**
Engine type	Diesel engine
No of cylinder	1
No of stroke	4
Cylinder diameter	87.5 mm
Stroke length	110 mm
Connecting rod length	234 mm
Orifice diameter	20 mm
Dynamometer arm length	185 mm
Power	3.5 kw
Speed	1500 rpm
Injection pressure	60 MPa
CR range	12:1 to 18:1

software (Ver. 9) was utilized to evaluate the engine performance and combustion characteristics. The first and foremost engine was first dedicated to diesel under no-load conditions. Then, the test was conducted on the diesel at different loads and constant speed of 1500 rpm. Similarly, the engine was fueled by B20, B20+25Al_2O_3, B20+50Al_2O_3, and B20+100Al_2O_3 in different load conditions (3, 6, 9, and 12 kg) and at a constant engine speed of 1500 rpm. The engine CR, injection pressure, and injection angle were calculated as 14, 60 MPa, and 30°bTDC, respectively.

3.2. Uncertainty analysis

Uncertainty analysis involves evaluating a set of inaccuracies experienced during the experimental process as well as other external elements. Such uncertainties in the results of the experimental analysis may be

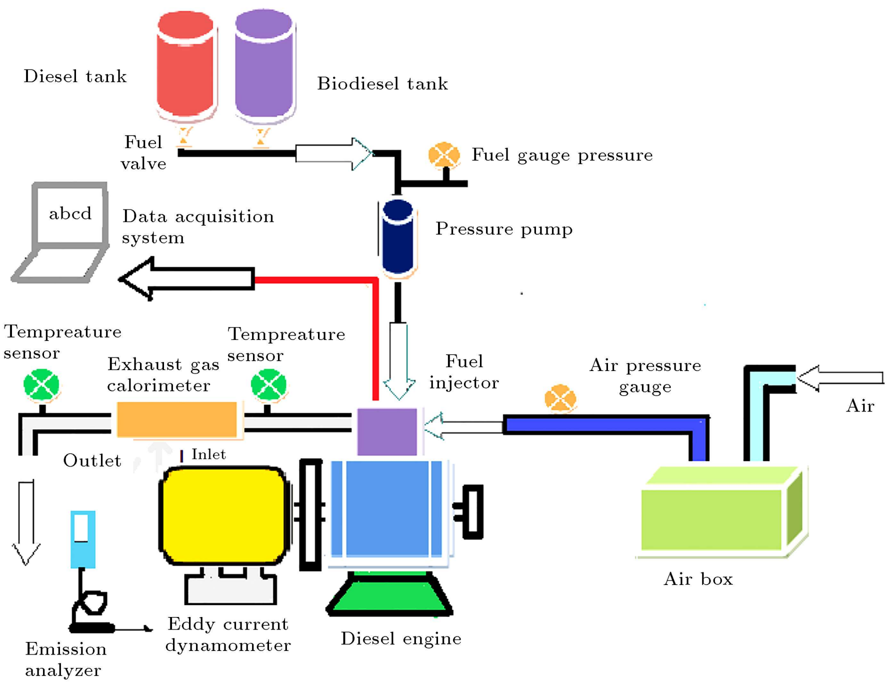

Figure 7. Block diagram according to biofuel engine setup in DTU lab.

Table 5. Uncertainty analysis of the obtained results.

Parameters	**Accuracy (±)**	**Uncertainty (%)**
Brake thermal efficiency	–	±0.4
Brake specific fuel consumption	–	±0.6
In-cylinder pressure	±0.2 bar	±0.3
Heat release rate	–	±0.55
CO emission	±0.01 vol %	±0.2
UHC emission	±15 ppm	±0.5
NO_x emission	±10 ppm	±0.7

more evident through the experimental setup, ambient condition for testing, engine equipment calibration, modification and adjustment of the engine setup, monitoring and instrument kinds, and testing procedures. The uncertainty analysis can reveal the precision of experimental tests. Essential measurement or estimation is the expected result of the test. The inaccuracies identified in the results share some similarities to the failure in calculating the resultant uncertainty of all unknown variables.

Repeatability precision is generally defined as a standard deviation of a mean result determined under some specific conditions where the same analyst makes a series of independent measurements of the test material with the same measurement system within a relatively short period. In this experiment, each test was repeated three times and their mean values were obtained. The error bar (I) graph at a confidence level of alpha = 0.05 is included in the "Result and discussion" section.

Table 5 presents the percentage of uncertainty in the measured parameters. In the current study, the approach presented in Eq. (1) was taken into account to calculate the uncertainty in the obtained data:

$$\frac{U_y}{y} = \sqrt{\sum_{i=1}^{n} \left(\frac{1}{y}\frac{\partial y}{\partial x_i}\right)^2}, \tag{1}$$

where y is the particular factor that is dependent on the parameter x_i and U_y denotes the degree of uncertainty or fluctuation in y.

Overall uncertainty (%) is equal to ± Square root of $[(0.4)^2 + (0.6)^2 + (0.3)^2 + (0.55)^2 + (0.2)^2 + (0.5)^2 + (0.7)^2]$. Total percentage of uncertainty is equal to ± 1.3%. The analysis of uncertainty can be done using Eq. (1). The total insecurity was calculated as ±1.3%, i.e., it was comfortably within the allowed threshold.

4. Results and discussion

4.1. Engine performance characteristics

4.1.1. Specific Fuel Consumption (SFC)

SFC is defined as the amount of fuel consumed per unit time which is necessary for providing the needed mechanical power on the engine shaft. Fuel consumption is correlated to the fuel properties such as viscosity, density, calorific value, and density. The fuel with higher viscosity has a lower calorific value than others, and the higher density of such a fuel is directly corresponds to its higher cetane number. Higher viscosity impacts the combustion behavior by their poor atomization, air-fuel mixing, air-fuel dispersion, swirl ratio, and penetration, which in turn affect the combustion attributes and engine performance [29]. According to the observations, B20 was characterized by higher BSFC than diesel under different load conditions mainly due to the lower calorific value of the fuel. To improve the physio-chemical properties of fuel to ultimately reduce BSFC, different concentrations of Al_2O_3 nanoparticles were added to B20. Considerable reductions in the BSFC, i.e., 2.6%, 5.13, and 9.24%, were observed in the ignition of B20 + $30Al_2O_3$, B20 + $50Al_2O_3$, and B20 + $100Al_2O_3$, respectively, compared to the B20 [30]. The minimum BSFC was estimated for Bi_2O_3 nanoparticle blended fuel rather than for B20. Expansion of Bi_2O_3 nanoparticles upgrades the heating value of the fuel, hence less fuel consumption for the same power generation on the engine shaft [31]. According to the observations, CeO_2 and MgO nanoparticles added to WCO biodiesel fuel reduced SFC as compared to diesel because nanoparticle additives reduced ignition delay and allowed for better ignition due to their high surface-to-volume ratio. In addition to better ignition, it led to less fuel utilization for the same power output [32]. Nanoparticle options diminish general energy consumption, while the opposite result can be expected depending on the sort of nanoparticle added [33]. SFC is reduced following an increase in the load, mainly due to the further development of the fuel combustion nature as the engine load increases [34]. As shown in Figure 8, SFC decreased gradually as the load increased, mainly because under low engine load, both heat transfer and friction loss in the combustion chamber were elevated. On the contrary, under greater engine loads, the engine power would increase. In addition, upon increasing the engine load, the thermal efficiency and combustion quality would be enhanced. These factors confirm

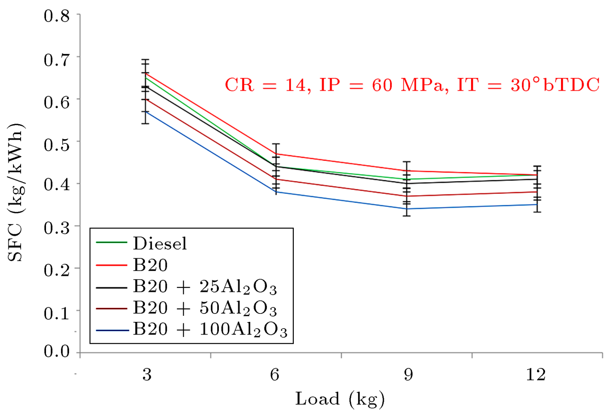

Figure 8. Specific fuel consumption with respect to load and error bar.

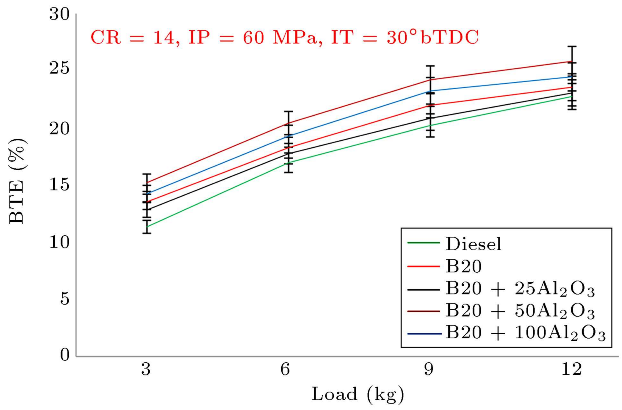

Figure 9. Brake thermal efficiency with respect to load and error bar.

SFC reduction in the engine under greater loads. Of note, the amount of SFC for B20 + $100Al_2O_3$ was lower than that for the diesel and B20 engines. Upon increasing the concentration of nanoparticles in the biofuel, the calorific value and ignition delay would considerably increase and decrease, respectively, hence lower SFC. Nanoparticles make the reactive surface region more exposed to air-fuel combination for heat transfer which, in turn, accelerates the evaporation rate of the air-fuel mixture, charges the reached auto-ignition temperature, and reduces the ignition delay period. Shorter ignition delays would increase the engine output even with the same amount of fuel consumption since once combustion gases are used, they will be diminished in the exhaust stroke of the engine. B20+$100Al_2O_3$ has the highest calorific value and a shorter ignition delay, hence the lowest value of SFC at all loads, compared to its counterparts. Addition of $Al_2O_3$100 in B20 led to a 20.93% reduction in the SFC value at maximum load, compared to that in the case of B20 alone. Of note, B20 is characterized by lower calorific value and longer ignition delay, hence higher SFC than other tested fuels.

4.1.2. Brake Thermal Efficiency (BTE)

BTE was used in this study to characterize the ability of the engine to transform the chemical energy of the fuel into valuable work. Of note, it increases gradually with an increase in the load, as shown in Figure 9. In addition, upon increasing the load, the heat loss and power are reduced and increased, respectively. The BTE value increases with an increase in the concentration of nanoparticles in the biofuel, which consequently enhances the fuel properties. This can be regarded as the most significant factor in evaluating the quality of air-fuel mixing ratio, air-fuel dispersion, fuel penetration, and ignition process. Modification of the fuel properties through the addition of nanoparticles is the best procedure to further develop the engine performance without modification of the engine design. Thermodynamics of combustion process, engine performance, and emission characteristics were assessed by exploring their belongings of different features including kinematic viscosity, heating value, flash point, density, and cetane number [35]. Al_2O_3 metallic nanoparticles scattered in the diesel methanol mix can enhance engine performance owing to their higher conductivity, higher surface-to-volume proportion, oxygen expansion, and catalytic functions. Experiments revealed that a 3.6% increment was observed in the BTE for 100 ppm Al_2O_3 nanoparticle additive fuel [36]. Given that since nano-molecules have a high surface-to-volume ratio, a more reactive surface area would take part in air-fuel blending [37], thus accelerating the evaporation rate of the air-fuel mixture, increasing the fuel droplet propagation, and injecting air-fuel dispersion. Nanoparticles are added to the fuel for better combustion and efficient fuel energy conversion. This high surface-to-volume ratio of nanoparticles and consequently, the increased heat transfer are the major causes of the rise in the power as well as the additional energy produced in the cylinder. Addition of nanoparticles would also decrease the ignition time and fuel combustion, hence more cylinder peak pressure and faster heat release [25,26,38]. Expansion of CERIA nanoparticles in the WCO (B20+CERIA45) would further enhance the BTE characteristics. Imperative increment of 10.5% in compare of base diesel fuel under the full engine load condition. Nanoparticles act as a catalyst in thermodynamics of ignition and accelerate the evaporation of air fuel mixture, which improves engine performance and discharges [39]. Al_2O_3 nanoparticles are characterized by high thermal conductivity and surface-to-volume ratio that contribute to the enhancement of air-fuel mixing, dispersion, fuel penetration, evaporation, and combustion temperature and pressure. Improvement of the combustion characteristics would reduce the ignition delay and enhance the engine performance. In all conditions, B20+$Al_2O_3$100 blend has the highest

BTE value among others including D100 and B20. It was reported that fuels' nanoparticle additives such as B20+25Al_2O_3, B20+50Al_2O_3, and B20+100Al_2O_3 contained 3.56%, 7.51%, 13.53% BTE, respectively, compared to the case of B20 in the full-load condition at 1500 rpm. Al_2O_3 addition would improve the calorific value of the test fuel samples, as shown in Table 3. Al_2O_3 nanoparticles are characterized by high thermal conductivity and surface-to-volume ratio which contribute to the enhancement of the air-fuel mixing, dispersion, fuel penetration, evaporation rate of fuel, and combustion temperature and pressure. Such improvement in the combustion characteristics would decrease the ignition delay and increase the engine performance.

B20 has the lowest BTE value due to its lower calorific value and higher viscosity of the fuel. Higher viscosity is the main cause of the poor atomization of fuel and poor air-fuel mixing, hence improper combustion. There might be a lack of effective conversion of fuel energy into useful work. This may be a reasonable explanation for the lowest BTE of B20 [40].

4.2. Combustion characteristics of diesel engine

4.2.1. Cylinder pressure

The cylinder pressure is an essential parameter in evaluating the combustion behavior in the combustion chamber as well as engine performance. According to the observations, engine pressure increased with an increase in the applied engine load. Under engine loads lower than 60%, less amount of fuel is injected which results in less ignition flame temperature and prolonged ignition delay. On the contrary, under higher loads, more charge is injected to the combustion cylinder as a result of which the cylinder surface and combustion flame temperature would increase, hence shorter ignition delay [41]. Expansion of nanoparticles in contrast with the neat biofuels is highly limited by the ignition delay. Assortment of fuel feedstock, nanoparticles, and their amount inside the burning chamber plays a considerable role in determining the ignition delay period. In addition, the ignition temperature and pressure, pre-ignition energy transfer, convection, and radiation to encompassing are the lengths of ignition delay period [42]. Figure 10 shows the relationship between the cylinder pressure and crank angle for several tested fuels at full load. The results indicated that cylinder pressure rose as the engine load increased, implying that much gasoline was injected and burned at greater engine loads. The graph shows that with lower biodiesel-diesel mixes, the pressure rises that began early at low engine loads. An additional content of Al_2O_3 in B20 produces higher in-cylinder pressure. Nanoparticles facilitate better fuel injection, proper air-fuel mixing, which results in

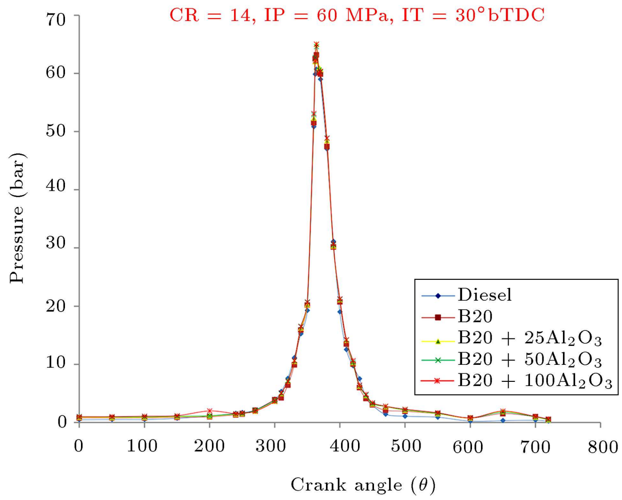

Figure 10. Cylinder pressure versus crank angle.

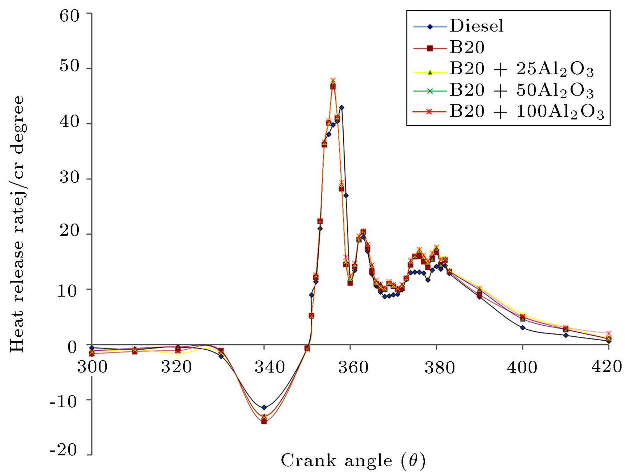

Figure 11. Heat release rate versus crank angle.

immediate absorption of latent heat to vaporize fuel, and the rapid propagation of flame, thus shortening the pre-combustion phase and ignition delay. As a result, much more heat accumulated in the premixed phase increased the cylinder pressure [26,38]. According to Figure 10, the cylinder pressure value of 60.81 bar was obtained at the crank angle of 8° aTDC for diesel. The cylinder peak pressures were calculated as 64.99 and 64.58 bars at the crank angle of 4° aTDC for B20 + 20Al_2O_3 and B20 + 50Al_2O_3, respectively. The peak pressure continued to increase to 65.02 bar for B20 + 100 Al_2O_3 at the crank angle of 2° aTDC.

4.2.2. Net heat release rate

The heat produced by the combustion blend at a certain angle is defined as HRR (the rate at which heat is released by the combustion flame). Figure 11 shows the rates of heat release at each angle of the paddle for the fuel tested at full load. In both biodiesels, HRRs had shorter ignition delays than that of the diesel. The HRR depends on the air/fuel mixture volume and quality, fuel heating value, and time-consuming delay within the pre-existing combustion chamber of the CI engine. The HRR of biofuel increased with increasing the mixing ratio of the air-fuel mixture when compared to diesel because biofuel contains more oxygen molecules than diesel. In addition, an increased mixing ratio decreases the viscosity of the air-fuel mixture. A mixture of air and fuel with less viscosity will promote better heat release. Use of diesel fuel on the CI engine will result in a longer delay in the ignition and an increase in the HRR within the fuel cell owing to its greater heat value. Addition of nanoparticles also increased the heat transfer rate of fuel. Higher thermal conductivity and reactive surface support fuel help reach auto-ignition temperature in the shortest time.

Premixed combustion period of fuel decreased as a result of the acceleration of ignition flame into the air-fuel mixture. Consequently, the ignition delay was reduced, and ignition was initiated earlier. Further, a huge quantity of energy aggregated in the premixed combustion mixture increased the heat release rate [43]. Addition of alumina nanoparticles to JB20D fuels increased gross heat transfer rate compared to the jatropha biodiesel without nanoparticles. Gross heat release rate affects the beginning of combustion, thus causing a delay in ignition period. The early initiation of combustion is attributed to the superior impact of the higher surface area on the volume proportion of alumina nanoparticles. Alumina nanoparticles upgraded the nature of fuel combustion, hence increased combustion pressure and gross heat transfer rate in comparison to JB20D blended fuel [22]. The net heat release rate for diesel, B20, B20 + 25Al_2O_3, B20 + 50Al_2O_3, and B20 + 100Al_2O_3 is shown in Figure 11 at full load condition. At the initial phase, fuel absorbs the latent heat of evaporation; in other words, heat is absorbed rather than released, which makes the heat release rate curve negative during this period. As the piston moved toward TDC, the pressure and temperature of the sample fuel increased. In the case of the B20 + 100Al_2O_3 fuel, the premixed heat release curve increases rapidly closer to TDC than B20 and diesel [43]. The values of HRR were obtained as 42.91, 46.71, 47.53, 47.71, and 47.91 J/degrees for pure diesel, B20, B20 + 25Al_2O_3, B20 + 50Al_2O_3, and B20 + 100Al_2O_3, respectively, at full load.

4.3. Emission characteristics

4.3.1. Carbon monoxide emission

The engine produces carbon monoxide on condition that the combustion cycle is not adequately oxygenated, and the fuel-air combination has enough fuel for combustion on the engine. Insufficient oxygen needed for converting carbon into CO_2 leads to unburned fuel and CO. Poor mixture, locally rich region,

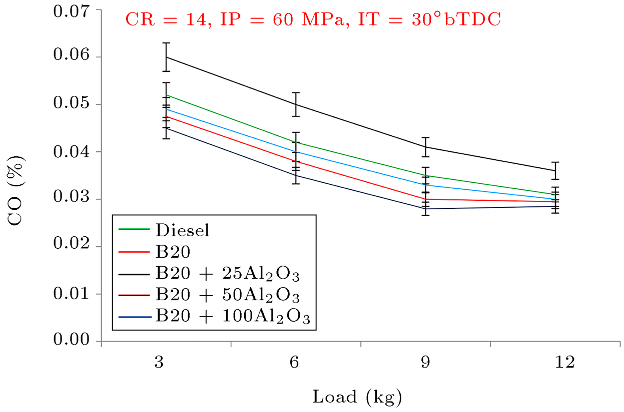

Figure 12. CO emissions with respect to load and error bar.

incomplete combustion, and insufficient oxygen are the leading reasons for carbon monoxide production. Internal combustion engines emit harmful emissions such as CO, CO_2, HC, NOx, smoke opacity, and PM [44]. Biodiesel blend in the diesel would reduce harmful emissions such as CO, HC, and PM [45,46]. CO emissions decreases as the load of engine increases for all fuel samples, as shown in Figure 12. However, the experiment revealed that CO emissions were elevated at full load. A significant reduction in CO emissions for B20 rather than in diesel was observed at all engine loads. Biofuel molecular structure contains O_2 molecules (WCO has 13.6% weight O_2 content) that leads to complete combustion at a higher temperature. The researcher analyzed the impact of Al_2O_3 nanoparticles as a fuel additive to diesel fuel on fuel atomization, air-fuel mixing, flame propagation, fuel spray, swirl ratio, fuel dispersion, fuel penetration, and ignition flame characteristics. Experimental evaluation revealed that alumina nanoparticle would increase the fuel penetration length, flame propagation, and thermodynamics of combustion, thus promoting complete combustion and reducing harmful emissions such as CO [47]. B20 + 100Al_2O_3 produced the least CO emissions at all engine loads. CO emissions are reduced when using Al_2O_3 nanoparticle with a diesel-biodiesel combination. Of note, addition of nanoparticles to the biofuel enhanced the fuel combustion characteristics, hence reduced harmful CO emissions mainly because nanoparticles could effectively oxidize the fuel. These results were confirmed based on the findings obtained in [48]. The wide surface area of Al_2O_3 increased the chemical reactivity and decreased the inflammation delay. Combustion was enhanced by reducing the ignition delay. Finally, the emission of carbon monoxide (CO) was reduced. In addition, the capacity of nanoparticles in converting CO into CO_2 by its powerful redox-active properties is an indicative of the reduction in CO emission from test fuels [49]. Compared to the case of B20, CO decrements in this case were 3.22%, 4.83%, 8.06% for B20 + $25Al_2O_3$, B20 + $50Al_2O_3$, and B20 + $100Al_2O_3$ fuels, respectively, at full load. Compared to diesel, the maximum reduction in CO emission was about 20.8% of B20 + $100Al_2O_3$, in full-load conditions, which was in accordance with the results from the literature.

4.3.2. Hydrocarbon emissions

More HC is produced as a result of incomplete combustion of fuel particles. Biodiesel contains higher oxygen content and less carbon and hydrogen than the regular diesel fuel, hence reduced HC emissions. HC emissions increased with an increase in the engine load. At higher engine loads, a greater mass of fuel will be injected to the combustion chamber to obtain a rich air-fuel mixture where more fuel will come into contact with the heated air, which reduces the evaporation rate of fuel droplets, meaning that there is not enough oxygen for combustion [50]. Addition of nanoparticles to gasoline mixes significantly reduces the hydrocarbon emissions. Nanoparticles act as a catalyst that enhance hydrocarbon oxidation and ensure full combustion. The nano-additive secondary atomization accelerates HC oxidation, hence reduced HC emissions. Fuel atomization in fuel injectors is enhanced due to the smaller size of nanoparticles.

Furthermore, higher fuel-air blending rates and proper combustion reduce HC outflows [51]. Scattering of nanoparticles with fuel upgrades, fuel atomization, and spray prompts appropriate air-fuel blending, acceleration of air-fuel heat transfer rate, and further developed burning, hence reduction of HC outflows [52]. Further, CeO_2 nanoparticles act as oxidating catalysts used for accelerating the oxidization process of charge and according to the results, harmful emissions such as CO and HC emissions as well as smoke opacity were considerably reduced [53]. Al_2O_3 is a metallic nanoparticle with a higher surface-to-volume ratio whose application guarantees the proper atomization, air-fuel mixing, air-fuel dispersion inside combustion. Furthermore, the mentioned nanoparticle acts as an oxygen donor in the combustion process, hence complete combustion inside the combustion chamber. Complete combustion means lower HC emission. At higher loads, diesel emits the higher HC level of 62% than that of B20. However, B20 + $100Al_2O_3$ produces about 28.94% more emissions than B20 under full load. The average values for the HC emissions predicted in all conditions were calculated as 11.8%, 22.36%, and 28.94% for the B20 + $25Al_2O_3$, B20 + $50Al_2O_3$, and B20 +$100Al_2O_3$, respectively, compared to B20 in full-load condition, as shown in Figure 13.

4.3.3. Nitrogen oxide emissions

Temperature and high activation energy are important factors in producing NO_X during fuel combustion.

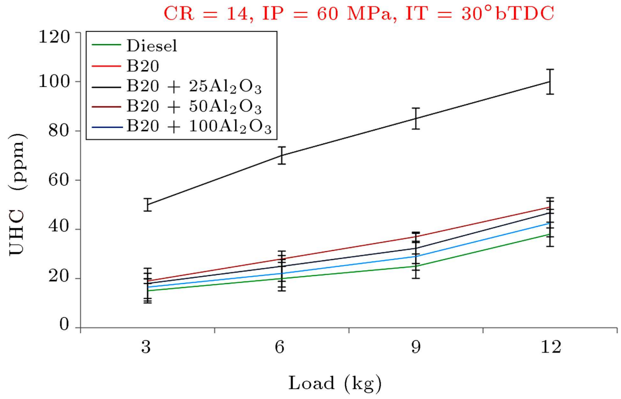

Figure 13. UHC emissions with respect to load and error bar.

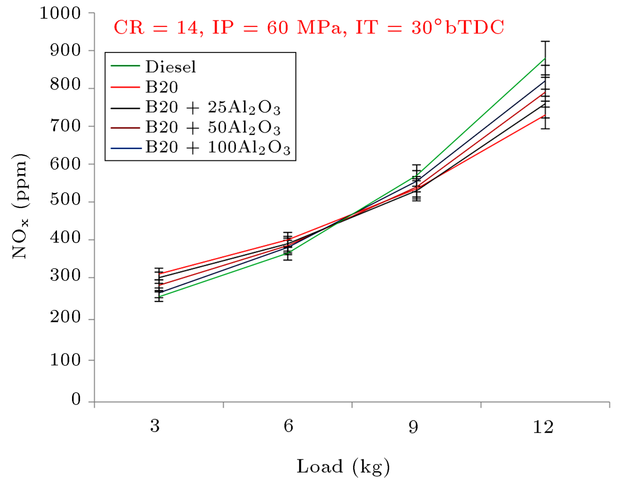

Figure 14. NO_X emissions with respect to load and error bar.

Owing to the high activation energy released from the high temperature, atmospheric nitrogen was converted into nitrogen oxides. In general, enhanced oxygen content of the biodiesel increases the temperatures during combustion, hence large amount of NO_X production. NO_X emissions gradually increased upon increasing the engine load for all tested fuels, as shown in Figure 14. At a higher load, greater fuel quantity is injected into the cylinder, hence higher combustion flame temperature. NO_X is produced at a higher temperature, and B20 causes higher NO_X emissions than D100 in full load conditions. B20 contains more O_2 which supports complete combustion at higher temperatures. The maximum increase up to 13.63% in the NO_X emissions of B20 + $100Al_2O_3$ was reported, compared to B20, under full engine load.

Unsafe NO_X emissions depend strongly on the temperature of the burning fire resulting from the expanded ignition response rate. As observed, at higher temperatures, HC and CO emissions were reduced [54]. Harmful NO_X discharges also increased since Al_2O_3 and CuO nanoparticles were considered as fuel added substances. Nanoparticles appear as oxygenated substances that facilitate further development of ignition and its temperature. Affected by the oxygenated additives and combustion improvement, NO_X emissions were reduced followed by an increase in the nanoparticle dosage. Addition of nano-metal oxide particles as oxygen catalysts resulted in full combustion. In this scenario, high peak pressure and maximum heat release can be predicted during combustion. Shorter nanoparticle ignition delays would in turn lead to lower premixed burn percentage, lower cylinder combustion temperature, and lower NO_X emissions [21,55]. Regarding the optimum concentration of Al_2O_3 additive in the biofuel, 100 ppm of Al_2O_3 blend in waste cooking biodiesel could ensure the maximum engine performance, improved combustion characteristics, and decreased emissions.

5. Conclusions

The main objective of the current research was to investigate the technical feasibility of using waste cooking palm biodiesel and waste cooking sunflower biodiesel as alternative biodiesel fuels to power a CRDI VCR diesel engine under different engine load circumstances. The parameters of the CI engine were tested at a constant engine speed of 1500 rpm with fixed CR = 14, IP = 60 MPa, and IT = 30° bTDC. The findings were compared to those of the diesel fuel engine. In addition, the present experimental study evaluated the impacts of Al_2O_3 additive to the supporting biodiesel B20 (WCPM 10% + WCSM 10%+ Diese l80%) on performance, combustion, and emission characteristics of the single-cylinder. The concluding remarks obtained from this experimental study are summarized below:

- Specific Fuel Consumption (SFC) of the nanoparticle-additive fuel (B20 + $100Al_2O_3$) decreased and BTE significantly, increased compared to B20 and pure diesel in all load conditions;
- Addition of nanoparticle Al_2O_3 to the biofuel increased the peak pressure, as in the case of B20 + $100Al_2O_3$ which had the highest peak pressure compared to B20 and diesel fuel. Apart from their addition of nanoparticles, B20 increased the heat release rate of the CI engine. The fuel sample (B20 + $100Al_2O_3$) had the highest elevated heat release rate compared to B20 and diesel fuel;
- CO and HC emissions were significantly reduced by adding Al_2O_3. In addition, B20 + $100Al_2O_3$ discharged the lowest CO and HC emissions among the B20, diesel and B20, diesel, B20 + $25Al_2O_3$, and B20 + $50Al_2O_3$ in all load conditions;
- However, there was a slight sustainable increment in oxidation of nitrogen emissions of CI engine fueled by B20 + $100Al_2O_3$, compared to B20 and diesel, in high load conditions.

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Abbreviations

ASTM	American Standard Testing Machine
aTDC	After Top Dead Center
B20	20% waste cooking oil + 80% diesel
BTE	Brake Thermal Efficiency
bTDC	Before Top Dead Center
CO	Carbon mono oxide
CPmax	Maximum cylinder pressure
CR	Compression Ratio
CRDI	Common Rail Direct Injection
HRRmax	Maximum heat release rate
IP	Injection Pressure
IT	Injection Timing
NO_X	Oxides of nitrogen
PPM	Part Per Million
SFC	Specific Fuel Consumption
TEM	Transmission Electron Microscopy
TDC	Top Dead Center
UHC	Unburned Hydrocarbon
VCR	Variable Compression Ratio
WCO	Waste Cooking Oil
WCPM	Waste Cooking Palm Methyl Ester
WCSM	Waste Cooking Sunflower Methyl Ester
XRD	X Ray-beam Diffraction

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