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# Micro explosion-Assisted Clean Combustion of Water-in-Algae Biodiesel Emulsions Tailored with Mono and Hybrid Nanoparticles

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## Abstract

The growing concern for efficient and cleaner diesel engines has led to the emergence of new fuels and advanced additives. This paper investigates the effects of mono and hybrid oxides. Aluminium Oxides ($Al_2O_3$), Cerium Oxides ($CeO_2$), biodiesel blended fuels B20 and water-emulsified B20W5 are incorporated in single-cylinder Direct Injection (DI) diesel engines. In this paper, an experimental study was performed to investigate the effects of ultrasonicated fuel blends on the engine parameters. A significant improvement has been observed in the peak Heat Release Rate (HRR) for $Al_2O_3$ compared to $CeO_2$, though in the case of $CeO_2$ the ignition was delayed but energy after ignition was improved. Hybrid fuels such as $Al_2O_3$ and $CeO_2$ were found to have improved ignition and 2-3% increase in the peak in-cylinder pressure compared to B20. The highest Indicated Mean Effective Pressure (IMEP) was produced by the blend of B20A with $CeO_2$ and water as 12 bar, 34% higher HRR, 54% higher heat release and 27% higher combustion speed. Also, its Indicated Thermal Efficiency (ITE) was 48%, which was much higher than that of B20. Furthermore, other observations show that $Al_2O_3$ and $CeO_2$ reduced the amount of Hydrocarbon (HC) and Carbon Monoxide (CO) emissions, and raised the amount of Nitrogen Oxide (NOx) and Carbon Dioxide ($CO_2$) emissions. B20A increased NOx emissions by 6% while B20C, B20AC, and B20ACW increased them by 29%, 18%, and 11%, respectively. A reduction in NOx was found at 7%, 15%, and 27% for B20W and B20WAC. In conclusion, the findings show that the addition of nanoparticles and water emulsification in bio-diesel fuels significantly improves engine performance, enhances engine thermal efficiency and decreases emissions from diesel engines.



**Keywords:** Nannochloropsis sp. microalgae; Aluminum oxide, Cerium Oxide; Diesel Engine; Emission

**Nomenclature**

$Al_2O_3$ - Aluminium oxide nanoparticle

AOME – Algae Oil Methyl Ester

B20 - 20 % biodiesel+ 80 % diesel

$B20Al_2O_3$ – B20A

$B20CeO_2$ - B20C

$B20Al_2O_3CeO_2$ - B20AC

$B20W5Al_2O_3$-$CeO_2$ - B20WAC

B20W - Water-in-biodiesel emulsion with 5 % water

BTE - Brake Thermal Efficiency

BTDC - Before Top Dead Center

CA - Crank Angle

CI - Compression-Ignition

CO - Carbon Monoxide emissions

$CO_2$ - Carbon Dioxide emissions

CHR - Cumulative Heat Release

HC - Hydrocarbon emissions

HRR - Heat Release Rate

IMEP - Indicated Mean Effective Pressure

ITE - Indicated Thermal Efficiency

LHV - Lower Heating Value

MFB - Mass Fraction Burned

$CeO_2$ – Cerium oxide nanoparticle

NOx - Nitrogen Oxides emissions

$O_2$ - Oxygen

PPM - Part Per Million

RPM - Revolutions Per Minute

SOI - Start of Injection

TDC - Top Dead Center

## 1. Introduction

The energy situation in the world is adjusted due to the acute necessity of renewing the exploitation of the scarce reserves of fossil resources and the role of the fuels on the environment. As a reaction to this demand, there has never been a serious necessity to establish clean and viable alternatives to energy as it is taken nowadays [1]. Even the sustainable vegetable oil and animal fat sources are not being left behind in the production of more biodiesel that is being increasingly promised as a viable alternative to the regular fossil fuels [2]. It is projected that the biodiesel market will expand by 68 billion next year because the industry will decrease by the year 2030 as compared to the growth that will be realized by the year 2025 of 44 billion that will be dominated by algae oil. In the production of the biodiesel, 20 % of the process uses algae oil in the development of the green energy and renewable energy [3]. The variations of the diversity of the fuel mixture with respect to diesel, biodiesel and hexanol were experimented upon the engine load under different loads in CI engine [4]. Its findings showed that the exergy of loss thermal and the exergy destruction at large was improved in the presence of hexanol which is an oxygenated compound. Specifically, at the full load diesel and the blend with 25 % of biodiesel and 50 % of hexanol exergy destruction were 15 kw and 17 kw, respectively. The problem can be solved by past research. To be more precise, it also turns out that there is a possibility that AOME usage will raise the fuel consumption rate by 15-20, and that the power generation speed will also go down by 10-15, as compared with the traditional diesel [5]. Based on the above presented difficulties, the experiment research currently being researched examines the feasibility of incorporating the properties of the hybrid nanoparticles into the water in biodiesel emulsions. The use of nanoparticles in the AOME composition is one of the new technologies of improving the properties of the fuel. The addition of the both $Al_2O_3$ and MgO would be inclined to favour the atomization of the material, enhance the performance of the catalysts with the ability of providing even higher burn intensity with reduced emissions to accompany the burn intensity [6]. The availability of $Al_2O_3$ will also tend to enhance the oxidation of the catalyst that will later translate to lessened ignition delay time and consequent increment in the transfer of the material to the surroundings once the material has undergone complete burning process. It is anticipated that the synergism would exist when the $Al_2O_3$ and MgO are applied simultaneously in order to become complete solutions. It shows that the $Al_2O_3$ might have a substantial capacity to reduce the harmful emissions in all the loads that were experimented [7]. These positive results show that aluminium oxide nanoparticles may be used to decrease the amount

of emissions and enhance the functionality of the engine effectively [8]. The uses of nanoparticle additives are also in demand, the AOME-to-water emulsification is also in demand as a potential remedy of converting the fuel into a more efficient and environmentally acceptable product [9]. This may be because there is a high likelihood that the fuel that has water in it can comfortably undergo micro-explosion of water in the combustion process [10]. It is a procedure of the swiftest achievable vaporizing the measure of drop of the water with the sudden rise in size, pressure that assists in the expansion of atomization and mix up of the fuel as well as the air [11-12]. This can be translated to complete enhancement of combustions; optimum temperature drops and minimization of the NOx emission and also investigated this case study to determine the effect of $Al_2O_3$ nanoparticles in addition of $Al_2O_3$ nanoparticles to an emulsified B20 blends of Pongamia bio-diesel in the presence of 5% of water [13]. It was also found that they enhanced BSFC, BTE and NOx emissions and this was not augmented by the reduction in the peak HRR. Increase in the combustion properties of BTE and BSFC was also found in the use of $Al_2O_3$ nanoparticles in another study. It was however observed that the rise in emissions of NOx was more in comparison with the neat diesel and B20 Bio diesel. It has increased further which has been attributed to the increase in full combustion leading to the increase of the emissions temperature [14]. All these advanced technologies, and in particular the incorporation of these numerous additives upon the foundation of the $Al_2O_3$MgO nanoparticles in water in-AOME emulsions is an intricate remedy to the issues of the conventional AOME. The complex of the innovations will be able to deliver the optimal increment to the effectiveness of the combustion, reduce the emissions. Consideration of stability of the blends is one of the best that can be taken concerning retention of the advantages of water emulsification over a longer period of time. It will entail also the incorporation of the involved surfactants which capitalize on the emulsification processes: the high-shear mixer application, the ultrasonicator [15-16]. The practice has also demonstrated that in the treatment of AOME-water, the right surfactants are employed which are. Span 80 combined with Tween 80 will cause the AOME-water emulsions to be relatively permanently adhered to at least a shelf life of more than a change a year [17]. The other issue of great effect that should be taken into consideration is the trade off, which is available between the low level of nitrogen oxide (NOx) emission against the potential high level of CO emission and the HC emission with inadequate combustion. It would necessitate the extreme sensitivity of water concentration optimization in this, whereby the engine operating condition and after-treatments of the exhaust would tradeoff in such a way that the required reduction in the emissions would be realized [18]. The earlier research has covered the AOME-water emulsions in the context of the metal-

based nano-additions on which it is expected that the toxic emissions are to be lower in case of metal-based nano-additions on the fuels. Although water-biodiesel emulsion may stand an opportunity to elevate combustion through the processes of micro-explosions and reduce the emission of NOx, owing to its reduced caloric value in the scenarios of high engine loads, in-cylinder pressure would decrease. Conversely, catalysts that are efficiently consumed following incorporation into nanosized particles are good catalysts of combustion because they have a good ratio of surface areas to volume and hence, they enhance the degree of fuel oxidation and total combustion efficiency. This is one of them since the $Al_2O_3$ material has been known to be a great conductor of heat and contributes to the maintenance of the high temperature in the ignition chamber and hence, the rapid quick combustion process. Equally, $CeO_2$ was found to have oxygen retention and discharge characteristics, which enhance oxidation reactions and further enable efficient combustion, which in turn limits the release of NOx [19]. The other possible materials that could be used as fuel additive are $CeO_2$ other than being cheaper than Magnesium and their high level of catalysis. The effect of $CeO_2$ nanoparticles on the operation of the SI engine in the case when it is a mixture of both ethanol and gasoline, which is used to create an ignitable substance [20]. Their results showed a 2.7 % rise in BP with addition of 10 % of ethanol. It is necessary to note that additional increase of BP by 14% and 19% during the supplementation by 10 ppm and 20 ppm $CeO_2$ nanoparticle were observed, respectively. It has also been demonstrated that water- biodiesel emulsions are capable of causing micro-explosion due to which the combustion efficiency is also increased and the production of NOx emissions is also minimized. The pressure in the in-cylinder would become inclined towards the bottom calorific value of emulsion fuel during heavy loads on the engine but at any rate the pressure in the in-cylinder. Specifically, the nanoparticles have gained much ground regarding the excellent physico-chemical characteristics of fuels, which also involves suppression of engine performance. The thermality of aluminate oxide ($Al_2O_3$) is very good and it contributes to the maintenance of the ranks of the combustion chamber at the high temperatures to benefit the complete combustion. Although the benefit of the $Al_2O_3$ and $CeO_2$ nanoparticles is individually analyzed, there is very little done on the effect of a combination of the two electrophiles especially when the water-in-biodiesel emulsions are used. They are not aware that the interactive composition of the aluminium oxide and cerium oxide nanoparticles in the event of the combustion and emission properties of water-emulsified algae-oil mixture had not been studied. In the experiment; the merits of a combination of a metropolis oxide an amalgamation of aluminium oxide ($Al_2O_3$) and Cerium oxide ($CeO_2$) and the addition of water was examined by utilizing algae-oil-processed biodiesel. Particularly, the experiment

under study attempted to determine the burning properties and accomplishment of emission of the use of algae-oil-derived biodiesel, supplemented with one and a blend of $Al_2O_3$ and $CeO_2$ (50ppm) and 5% water emulsions. The experiment prepared by the investigator was direct injection diesel engine which happened to be 4-stroke 1500 rpm, full load engine. Generally, these additives had caused a rise in the combustibility and emission profile in all the samples of tests.

## 2. Materials and Methods

### 2.1 Preparation of fuel blends

The provided analysis has compared various fuel mixes, i.e., biodiesel mixtures, water-bead mixtures as well as formula mixtures with nanoparticles added to them. The calorific value, surface tension, viscosity, and innermost density of all the reviewed fuel were found in the advanced analysis equipment. Density was determined with density meter (DMA 35) and the viscosity was determined with viscometer (Brookfield LVDV2T). The tension of the surface was identified in pendant drop technique in KRÜSS Drop Shape Analyzer and Calorific value was identified in calorimeter (IKAC 200). Table 1 has the specifications of all the fuel tests done. The purities of the $Al_2O_3$ and $CeO_2$ are 99.5 prevalence and 99.2 prevalence respectively and size of the particle are 70 nm and 40 nm respectively.

**Table 1. Properties of fuel blends**

| Properties | B20 | B20A | B20C | B20AC | B20W5 | B20WAC |
|---|---|---|---|---|---|---|
| Density (kg/m³) @ 25 °C | 845 | 847 | 849 | 851 | 855 | 861 |
| Kinematic viscosity (mm²/s) @ 40 °C | 2.57 | 2.7 | 2.64 | 2.66 | 2.67 | 2.86 |
| Surface tension (mN/m) @ 25 °C | 30 | 31 | 32 | 33 | 33 | 36 |
| Calorific Value (MJ/kg) | 45.87 | 45.6 | 45.32 | 45.2 | 43.97 | 45.52 |

### 2.2 Emulsion preparation

Fig. 1. shows the in-biodiesel fuel blend in water of the emulsion fuel prepared with the help of nanoparticles of Alumina ($Al_2O_3$) and Cerium oxide ($CeO_2$). The emulsion in this instance was prepared in ultrasonic homogenizer that comprised of 94 % algae- based biodiesel, 1 % members of the surfactant, Span 80 as well as 5 % of the volume of water (5 % w). One of the measures of emulsion stability was the phase separation, which was crudely investigated. The stability and the HLB of Span 80 are examined in details since they were indicated in the previous studies [21]. It was established that gravitational and centrifugal analyses established that all the emulsions are stable even after 24h. Fig. 1. illustrates the in-biodiesel fuel mix in water of the emulsion fuel formed with the assistance of the nanoparticles of Alumina ($Al_2O_3$) and Cerium oxide ($CeO_2$). In this case emulsion was made in ultrasonic homogenizer which consisted of 94 % algae-based biodiesel, 1-% members of the surfactant

namely, Span 80 and 5 % of the volume of water (5 % w). The phase separation was one of the emulsion stability measures and crudely studied. The evaluation of the stability and the HLB of Span 80 is discussed in details, as it was pointed out in the previous studies [22]. The centrifugal and the gravitational analysis had determined that all the emulsions were stable after 24h at the same time.




Fig. 1. Preparation of emulsion fuel blend

## 3. Experimental set-up

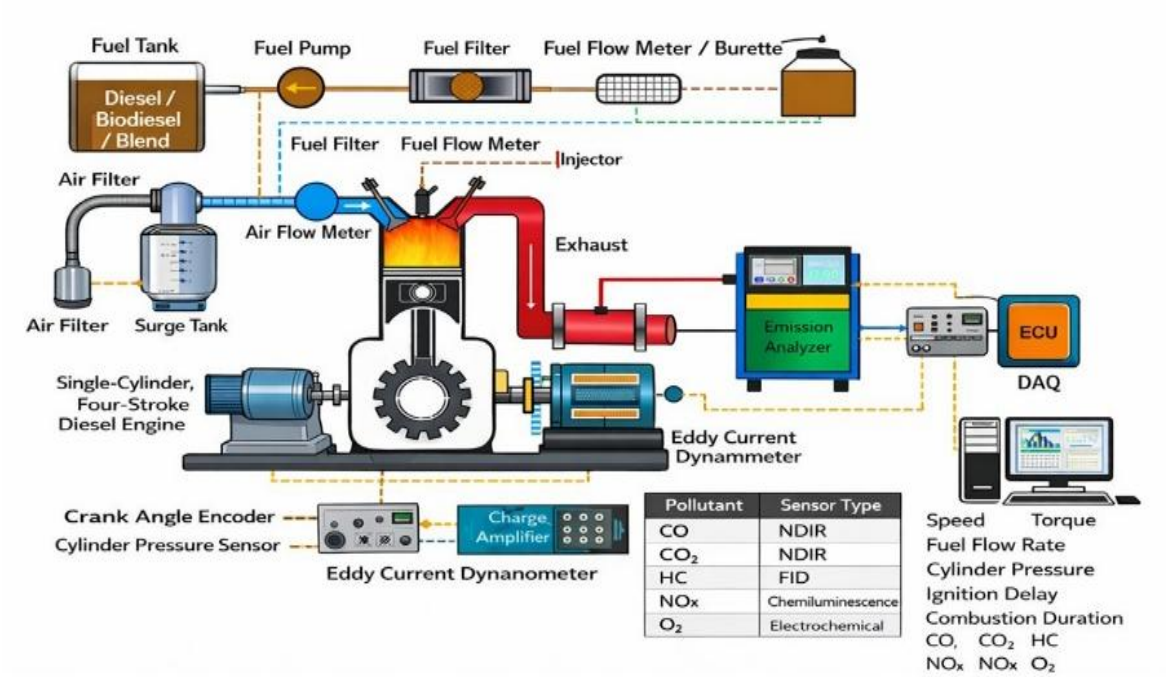



Fig. 2. Diesel engine test rig

The experiments were completed with a Kirloskar AV1 Diesel Engine diesel engine. This motor was coupled to an eddy current dynamometer, which could deliver 5.2 kW, up to 28 Nm torque and a 1500 rpm. Table 2 shows a summary of the technical information in the

engine. Fig. 2 is a schematic view of the test rig including the main constituents and the actual experimental arrangement. Table 3 shows a engine instrument accuracy.

| **Table 2. Engine Specification** | |
|---|---|
| Parameter | Specification |
| Engine Model | Kirloskar TV1 |
| Engine Type | Single cylinder, four-stroke, water-cooled, direct injection diesel engine |
| Aspiration | Naturally aspirated |
| Bore × Stroke | 87.5 mm × 110 mm |
| Displacement Volume | 661 cc |
| Compression Ratio | 17.5 : 1 |
| Rated Power | 5.2 kW |
| Rated Speed | 1500 rpm |
| Maximum Torque | 28 Nm @ 1500 rpm |
| Number of Cylinders | 1 |
| Stroke Type | 4-stroke |
| Cooling System | Water cooling |
| Fuel Injection System | Mechanical direct injection |
| Injection Timing | 23° before TDC (typical) |
| Injector Opening Pressure | 200 bar (typical) |
| Dynamometer | Eddy current dynamometer |
| Loading Type | Computerized data acquisition system |
| Combustion Chamber | Hemispherical open combustion chamber |
| Fuel Type Used in Study | Diesel / Biodiesel blends |

| **Table 3. Engine instrument and accuracy** | | |
|---|---|---|
| **Measuring instrument** | **Range** | **Accuracy** |
| Pressure gauge | 0–200 bar | ± 1 % |
| Thermocouple (K-type) | 0–1100°C | ± 0.1 °C |
| Torque measuring instrument | 0 ± 100 to 0 ± 5000 Nm | 0.05 % |
| Fuel flow burette | 0–100 ml | ± 1 % |
| Crank angle encoder | 0–360° | ± 1 % |

Measurement error is extremely critical in determining correctness and dependability of experimental data. This study identified some of the sources of uncertainty as well as considered their impacts that can be caused on measurements. The error of 1.8 % is the largest error and its effect can affect the transient engine parameters with the uncertainty of time measurement of ±1s. Engine speed with a variation range of ±10rpm leads to the development of a 1 % uncertainty which could affect performance calculations. Torque results of ±0.2 Nm error of 1.4 % is inclusive of accuracy, and influences power and efficiency calculations. Furthermore, the imprecision of the measurement of pressure is ± 0.01 bar that can be

converted into an error of 1 % that can disrupt the heat release rate calculation which is approximated as having an error of ±0.24 %.

## 4. Results and discussion

### 4.1 In-cylinder pressure

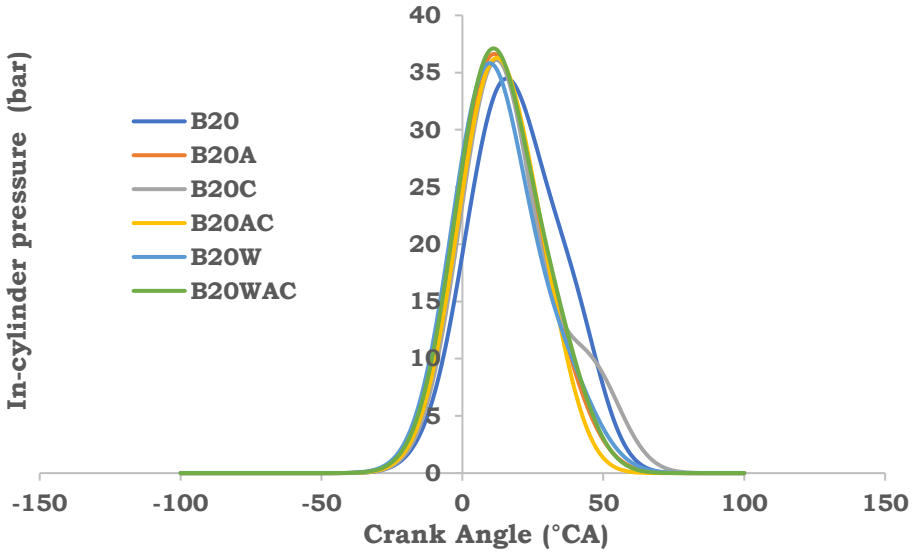



Fig. 3. Effect on In-cylinder pressure

Fig. 3 shows the variation of in-cylinder pressure at load. The insertion of nano-additives yields amazing variations in peak pressure and time of combustion. Specifically, a significant improvement in the onset of high peak pressure and combustion is apparent with the addition of aluminum oxide ($Al_2O_3$). An example of this would be the fact that a pressure rise, once -14°CA (6 bar) to 7°CA (32 bar) occurs which culminates in a maximum pressure of 35 bar as -14°CA (32 bar). This is a 3 % more peak pressure growth through a configured combustion improvement of about 12 °CA in comparison to the base fuel (B20). The identified change in the timing of combustion indicates that $Al_2O_3$ improves the ignition properties by increasing the fuel reactivity [23]. However, when Cerium oxide ($CeO_2$) is added to biodiesel (B20 + 50ppm $CeO_2$), the trend in combustion is similar to base fuel and the peak pressure is slightly higher 36 bar at 26°CA, which is an improvement of 3%. A low increase in combustion time relative to $Al_2O_3$ indicates that $CeO_2$ does not affect much the ignition delay but only increases the rate of energy release. The presence of 50 ppm of $Al_2O_3$ and $CeO_2$ in biodiesel (B20AC) indicates that the maximum pressure of 36 bar will be attained at 13 °CA which is 3 % better than B20 and results in a better time of maximum pressure at around 14 °CA due to the activity of $Al_2O_3/CeO_2$ nanoparticles. The combustion is promoted by the addition of water and the peak pressure is increased [24]. The same trend appears in blends B20W and B20WAC,

whereby B20W involves a maximum of 35 bar at 14 °CA (3 % rise and 12 °CA (before TDC) and B20WAC blends (maximum of 36 bar at 12 °CA) or 12% (before TDC). The 1 % lower peak pressure (35 bar) but 14 concentrated on less caustic soda previously with the B20W emulsion blend can be justified by its lower calorific value and the premixing caused by the micro-explosion. This is to ensure a complete combustion because all blends are stabilised at 90°CA, and this satisfies the objective of reducing the non-burning hydrocarbon emissions. The improved reaction kinetics and flame growth found with additive-blended fuels (advanced peak pressure timing) may be explained by the use of better atomisation and catalysis of nanoparticles [25].

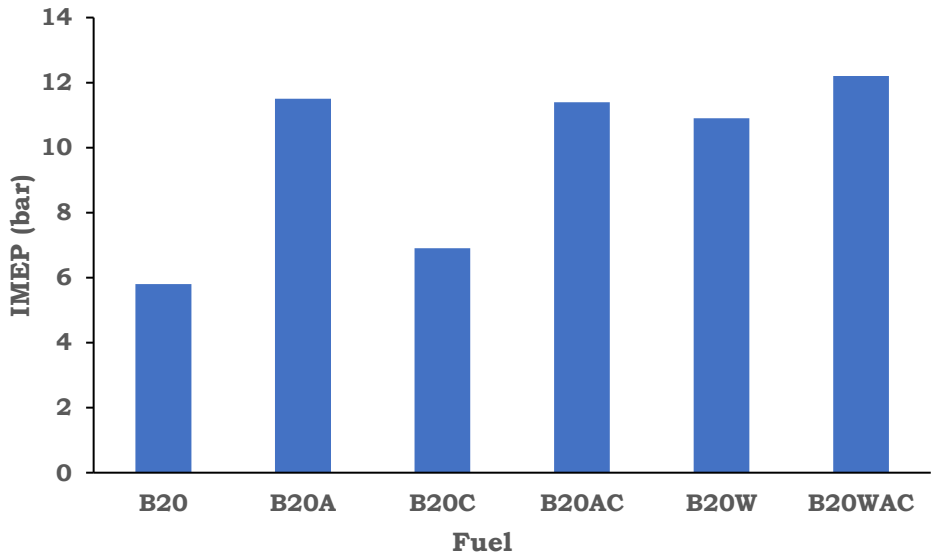



Fig. 4. Indicated mean effective pressure

All the tested fuels were computed with the IMEP summarized in Fig. 4. The standard of performance of B20 blend is IMEP = 5 bar. Conversely, additions with nanoparticles additions offer huge advantages. The blend containing aluminium oxide and Cerium oxide in the presence of water (B20WAC) produced the highest IMEP of 13 bar then B20A with 12 bar. However, the mixture containing pure Cerium oxide alone (B20C) was the lowest IMEP, which shows that Cerium does not contribute significantly to the combustion performance on its own. The emulsified mixture, B20W, in water was measured as 12 bar IMEP, which shows that it is practically difficult to raise IMEP using water emulsion. The combined effect of secondary atomization due to water [26], improved combustion in the presence of nanoparticles and the load dependent fuel-air mixing effect results in a change in the combustion regime that results in the shape of the pressure profile similar for the IMEP.

### 4.2 Heat release rate

The profiles of HRR of de-addition mixtures of biodiesel presented in Fig. 5 exhibited some distinct patterns of combustion in relation to the fuel blend and additives. It is notable to mention that the data in the figure are smooth with a moving average of 5. The HHR curve represents the oscillation phenomena in the fuel injection and initial fuel-air mixture phase in stage one and the endothermic fuel evaporation in stage two pre-combustion phase [27]. The formation of exothermic combustion is gradual, and it suddenly leads to the increase of HRR at the main combustion phase.

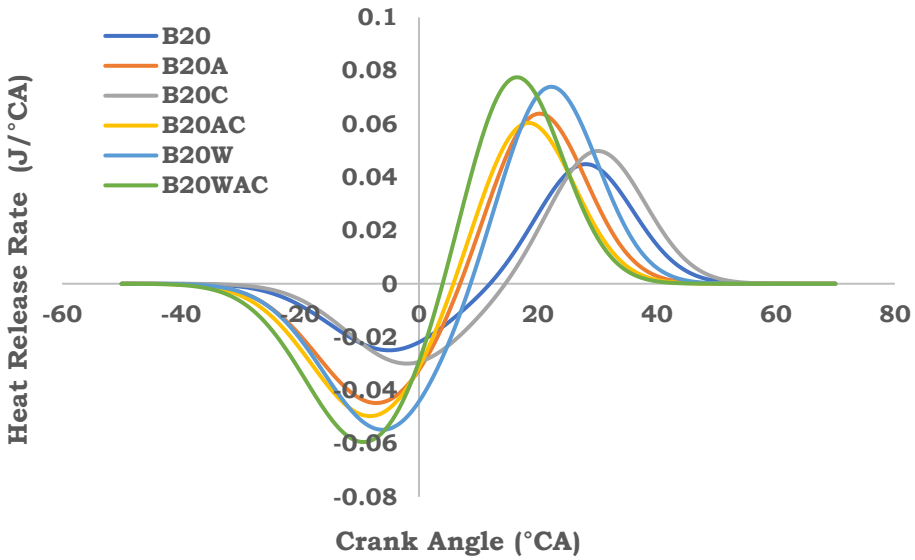



**Fig. 5.** Effect on Heat Released Rate

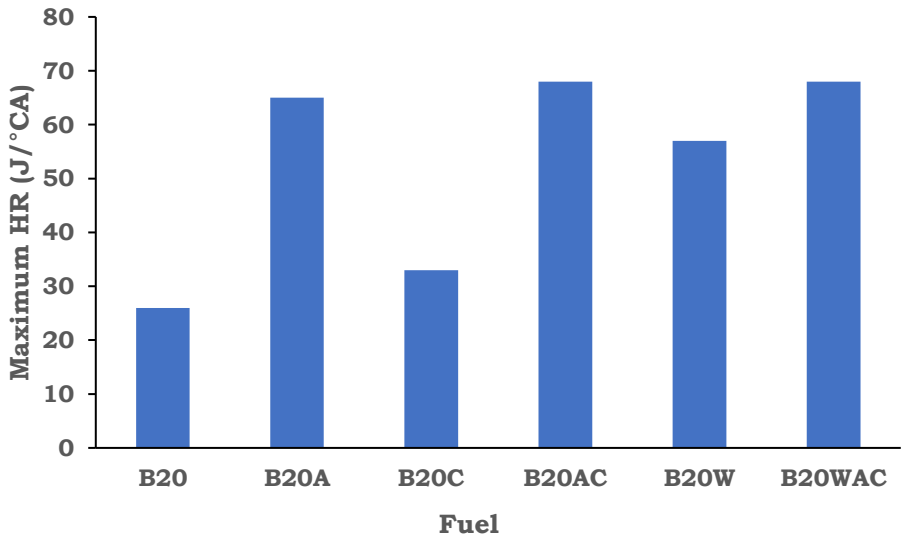



Fig. 6. Maximum heat release

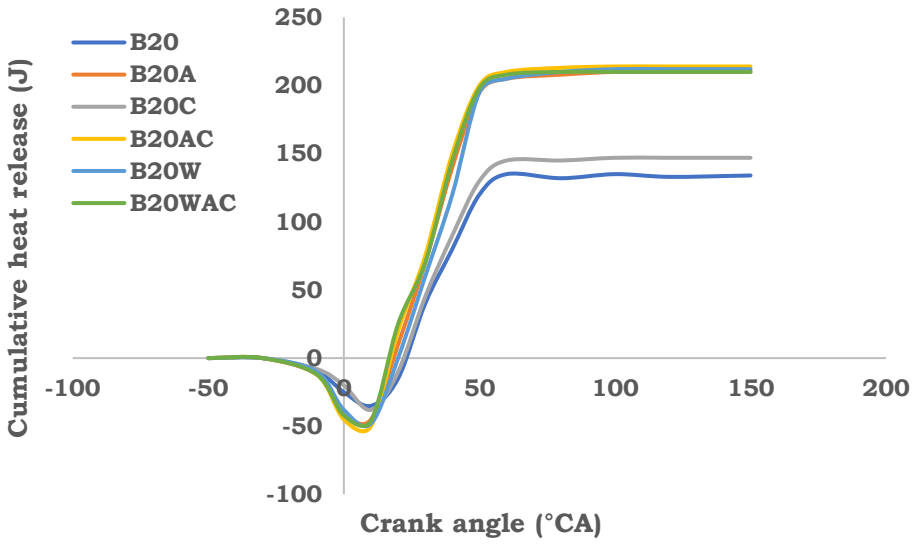



Fig. 7. Cumulative heat release

The maximum HR is shown in Fig. 6. It can be observed that the highest HRR is recorded in B20 (27 J/°CA at 28 J/°CA) as compared to all the other fuels tested. The introduction of the alumina oxide (B20A) shows a peak HRR (65 J/°CA) even greater, by 146 %, than the fuel (B20) itself with gentler transitions and long-duration diffusion combustion, which is associated with the thermal conductivity of alumina oxide and the catalytic action. However, with the addition of Cerium in B20C, the vaporization and combustion are improved, with 25 % higher HRR (33 J/°CA) than B20, but less HRR (61 J/°CA) than B20A, and delayed peak HRR (30 J/°CA) implying better diffusion combustion [28]. The addition of Cerium to B20A (B20AC) also increases the max HRR and attains the highest peak HRR (69 J/°CA) by taking advantage of the combined effects of nanoparticles and continuous diffusion combustion. The combustion HRR is enhanced by water (B20W) addition for atomizing, with higher HRR (58 J/°CA) than 27 J/°CA with B20 because of micro-explosion, but shorter diffusion time to release energy. However, the addition of water to B20AC attains the same HRR (69 J/°CA), good combustion, better pre-ignition mixing, faster rise in HRR, better diffusion stability, and improves the energy release [29]. The nanoparticles may have increased the oxidation of the fuel combustion at high temperatures, and decreased the water-cooling effects on mixture, enhancing combustion. The Cumulative Heat Release (CHR) curves for baseline B20, B20A, B20C and B20AC (nanoparticles dispersed in biodiesel) additives, B20W emulsified blend with water and B20WAC triple additive (mixture of water emulsion and two kinds of nanoparticles) are presented in Fig. 7. The CHR obtained from a 2D-integration of the net HRR, is a useful indicator of energy conversion as a function of the crank angle. The figure is obtained from a sequence of combustion events that start to gain heat (heat release rate is -20°CA), due

to pre combustion and premixed combustion main stage and moves to the stabilized point. The point of the baseline B20 has a late phase and the heat release is very low (0.20 J), with a negative endpoint of -35 J at about 18°CA. In the main period (26°CA to 76°CA) there is a rise to reach the stable maximum value of 137 J. The peak rate of increase in heat is 23 J/°CA at 28°CA, 32 °CA and the average rate of increase is 5 J/°CA during the main stage. The peak CHR of B20A, B20W and B20WAC, is about 211J at 76° C. For example, the B20W mixture emulsified with water presents an earlier start of the main process (20 % earlier), lower maximum value of -50 J (45 % lower) and increased positive maximum value of 213 J (57 % higher) with respect to B20. It has an improved range of total heat release by 54%, maximum release rate by 21% to 28 J/°CA total and the stationary heat release rate by 45%. The B20WAC, blend with triple additives, is the best performing mixture. It promises a reduction of the start of combustion of 24 that is the base with the maximum negative (-48 J) heat release (40% lower) and the maximum positive (211 J) heat release (55% higher). Heat release is 259 J, or 52% higher than B20. The highest heat release rate is 31 J/°CA, (35% higher) at a particular height in the improvements in the mean rate of 64% accompanied with a reduction of the burning period of 28%. The results indicate that the water emulsion and double nanoparticle additive needs to be catalytic, and improved heat loss, improved reaction rate and improved thermal efficiency to use the micro explosion (and possibly catalytic) effects. The triple-additive system creates a faster reaction rate, better heat transfer and lower burning period than single-additive blends, the best method for enhancing biodiesel combustion [30].

**4.3 Mass Fraction Burned**

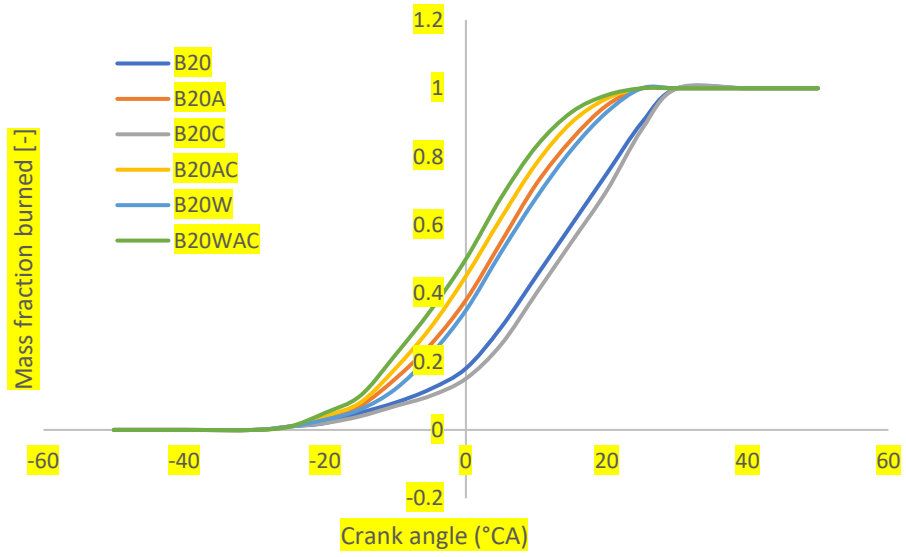



Fig. 8. Mass Fraction burned

MFB is calculated by taking the cumulative HR/full cumulative heat release. One of the most important parameters to analyze the features of combustion involves MFB, which helps to examine the ignition delay. Fig. 8 shows the influence of $Al_2O_3$ and $Ceo_2$ and a mix of both $Al_2O_3$ + $CeO_2$ with water and without water on the MFB in comparison with B20. The first is the gradual rise (0-10%) of the MFB owing to combustion premixing with fuel evaporation and mixing taking the preponderance. It is then succeeded by a sharp increase (10%-90%), as diffusion-dominated combustion becomes more intense and increases energy emission. The last stage (90 % -100 %) exhibits a lower rate of burn because of extinguishing the flame and the low fuel supply. The timing of ignition, which is the crank angle during which 10% of the fuel mass fraction is exhausted during combustion (MFB20) is an important factor in defining the combustion properties and efficiency. The ignition of the B20 blend (baseline fuel) in this research is -2°C. B20A and its ability to enhance the ignition timing to much an earlier time of -12°CA mediates the ignition catalytic influence of the $Al_2O_3$ nanoparticles in stimulating the kernels of the flame to form earlier and to help with enhancing chemical reactions. The credit of an increase in the ignition behaviour may be accredited to an increase in the oxidation property of $Al_2O_3$ as well that promotes the breakdown of fuel and propagates the flames more readily [31]. On the other hand, addition of $CeO_2$ nanoparticles (B20C) causes a reduction in ignition delay by 50 % that of B20 to 1° CA. It is possible that slower ignition was brought about by the lower thermal conductivity of $CeO_2$ and the possibility of interference by the initial radical generation, even though the catalytic quality of $CeO_2$ was useful. This implies that $CeO_2$ promotes more advanced stages of burning and not the first stage of ignition. The B20AC and B20A blend (mixed with both $Al_2O_3$ and $CeO_2$ nanoparticles) ignites similarly to B20A, followed by a further development to -12° CA (450 % improvement over B20). This implies that the ignition characteristic is mainly influenced by the presence of $Al_2O_3$ whereas post ignition combustion enhancement is mainly influenced by $CeO_2$. The synergies between these nanoparticles result in an increase in fuel and air mixing as well as accelerated flame spread. The use of 5% water emulsion (B20W) delays the start of combustion by 350% to -9°CA compared to B20. But, in case of the water-emulsified mixture to which nanoparticles were added (B20WAC), ignition timing is brought forward to -13°CA, which is an improvement of 550 % relative to B20. This implies that the trend of water cooling can be compensated by the catalytic activity of $Al_2O_3$ and $CeO_2$ which have the effect of increasing oxidation and reaction kinetics [32]. It is probable that nanoparticles contribute to the formation of a faster radical, which would decrease the ignition delay due to the vaporization of water. The mass fraction burned (MFB), 10% to 90% mass fraction burned is a key variable that can

be measured to establish combustion efficiency and fuel blend performance. In the study, the B20 fuel has burned 100 % (90 % MFB) at 24°CA ATDC and serves as the baseline. The use of nanoparticles is also believed to have a major effect on combustion. The B20A fuel mix experienced 90 % MFB at 18° CA ATDC, which was earlier than B20. This is a 30 % reduction in the duration of combustion that can be attributed to the higher thermal conductivity and the catalytic properties of $Al_2O_3$ nanoparticles that increase the speed of the flame. Similarly, the duration of combustion of B20C was found to be the same as that of B20 at 25°CA ATDC. Therefore, $CeO_2$ did not have a significant effect on the duration of combustion, this is likely due to its oxidation property that may not increase the flame speed as much as $Al_2O_3$. The combination of the two nanoparticles (B20AC) had a shorter duration of combustion with 100 % combustion occurring at 17°CA ATDC, which accounts for a 39 % decrease in the duration of combustion with B20. The synergistic interaction of the $Al_2O_3$ and $CeO_2$ could have contributed towards the increased turbulence and better oxidation of the fuel which promotes the speed and rate of the oxidation process. Moreover, B20W (containing 5 % of the water quantity) was able to reach full combustion when 20°CA ATDC, therefore, lessening the burning duration by 27 %. The occurrence of water micro- explosions might have facilitated the second-order atomisation and a higher degree of mixing between the air and fuel, which created faster combustion [33]. The mixture considering B20WAC with the highest completion rate in terms of burning time was 15°CA ATDC, with a 42 % burning time. The results of the reduction in the combustion length of the nanoparticle-added water-bearing fuels are indicative of increased fuel reactivity, improved flame propagation and air-fuel mixing, and are all positive for engine efficiency and low emissions.

**4.4 Indicated thermal efficiency**

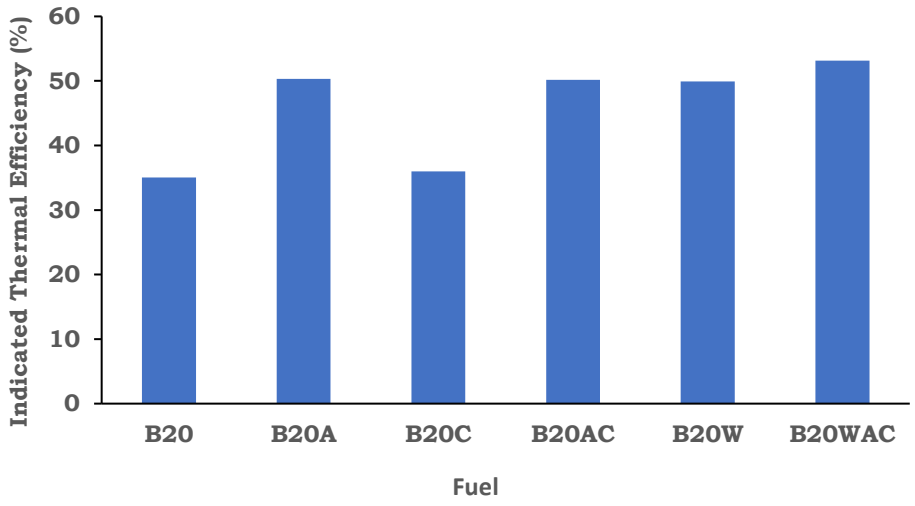



Fig. 9. Effect on Indicated Thermal Efficiency

The ratio of the indicated power with the input or heat energy of the fuel supplied is known as indicated thermal efficiency (ITE). Fig. 9. shows the influence of biodiesel and the nanoparticle combination emulsions on ITE for different fuels. The figure shows that B20 blend (without additives and without water emulsion) has the lowest ITE of all tested fuels, which is around 27%. This should be the case since pure biodiesel-diesel mixtures have generally high viscosity and low volatility which result in incomplete combustion and losses of heat [34]. The incorporation of $Al_2O_3$ nanoparticles enhances ITE into 45 % in comparison to B20. This can be attributed to the fact that the $Al_2O_3$ improves the combustion via catalytic oxidation leading to an acceleration of the flame velocity and the thoroughness of combustion. Enhanced thermal conductivity of $Al_2O_3$ enhances transfer of heat resulting to less heat losses. In the case of $Ceo_2$, ITE is small in comparison with B20 and this indicates that $Ceo_2$ is weakly acting as compared to $Al_2O_3$. The $Ceo_2$ is a catalyst, yet has a small potential to slow down ignition and to slow the combustion rate, decreasing the potential efficiency gains. The partial oxidation of cerium-based compounds may also play a role in the loss of residual energy [35]. The mixture of $Al_2O_3$ and $Ceo_2$ does not demonstrate a considerable improvement in comparison to B20A. $Al_2O_3$ has the dominant effect and $Ceo_2$ might not make an important contribution to efficiency. The potential of interaction between nanoparticles may be limiting future benefits. ITE is raised to the range of that of B20A when water emulsion (5 % water) is put in. The micro-explosive effect of droplets of water enhances the process of subjecting fuel to atomization, which is guaranteed to achieve a better mixture of air and fuel. Water will cause the reduction of the peak combustion temperature resulting in reduced losses of heat and higher efficiency. The rapidity of combustion kinetics compensates the cooling impact of water. particles, which make a thermal efficiency to be optimized. The nanoparticle is effective in enhancing ITE and $Al_2O_3$ is more effective as compared to $CeO_2$. Water emulsion will improve ITE by decreasing the heat losses and enhancing atomization [36].

### 4.5 Nitrogen oxide (NOx)

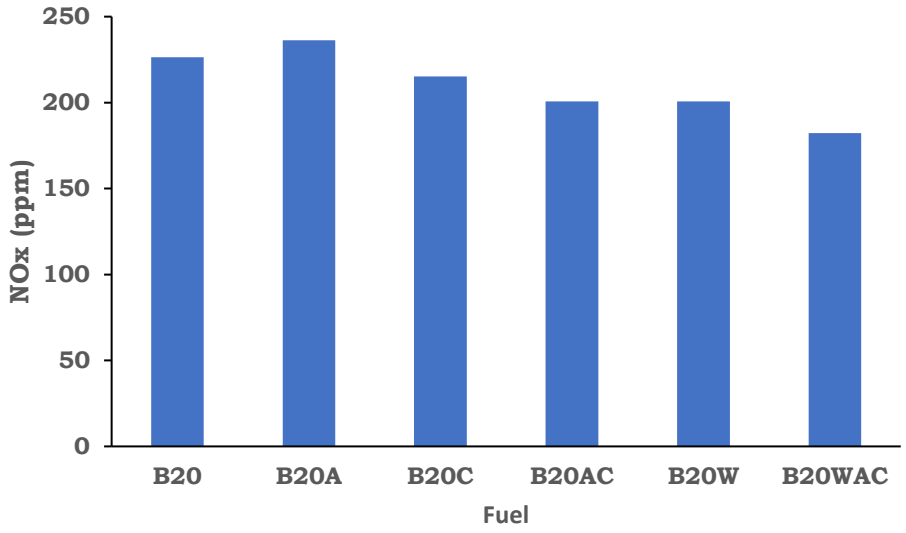



Fig. 10. Effect on NOx emission

Fig. 10 shows the emissions of NOx at full load in the various fuel mixes wherein NOx is a combination of NO and $NO_2$ emissions. The increased fuel consumption of high loads increases in- cylinder temperatures, which increases NOx formation. The addition of $Al_2O_3$ to B20 slightly increases NOx emissions (6%) perhaps due to the high thermal conductivity of $Al_2O_3$ which is useful to combustion and heat transfer that increases the flame temperatures and therefore, enhances NOx formation. Moreover, $Al_2O_3$ is not particularly active in the reduction of NOx and actually does not decompose NOx. Nevertheless, it has a large surface area that enhances oxidation, elevation of flame temperature, reduction in the amplified combustion pressure and ignition delay, all of which raise the level of NOx buildup. Alternatively, the $CeO_2$ NPs improve the decrease of NOx emissions by 7% through the ability to carry $O_2$ and catalytically stabilize the combustion of different fuel opposites so that the combustion involves a higher portion of complete combustion [37]. The hybrid types of nano-particles ($Al_2O_3$ +$CeO_2$) and water-biodiesel (B20W) further reduce the NOx by 16%. The evaporation of water absorbs heat from the combustion process and reduces the peak flame temperatures and subsequently, thermal NOx. The water emulsification process also leads to better fuel atomization and air-fuel mixing, which in turn leads to better combustion and lowers the NOx hot spots. Specifically, the NOx emissions for B20A, B20C, B20ACand B20WAC increased by 7, 8, 16 and 28 % respectively [38].

### 4.6 Hydrocarbon

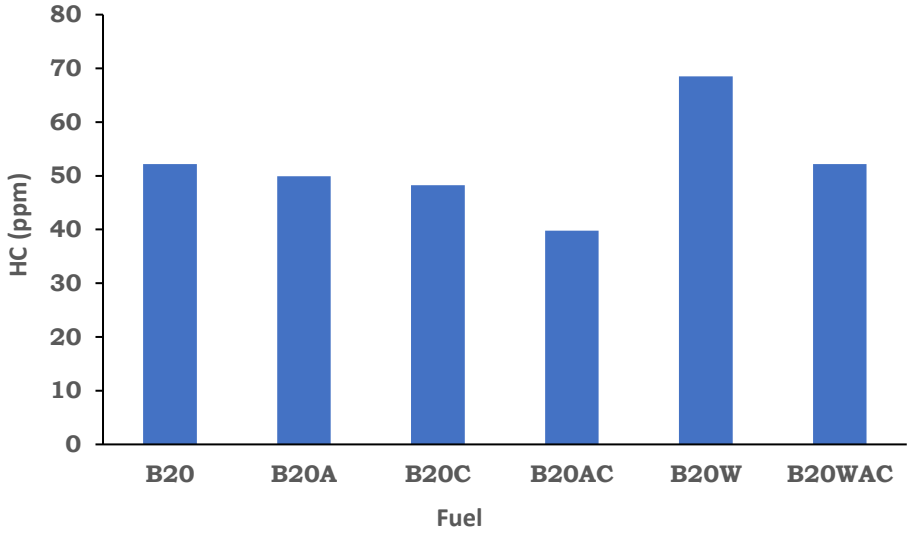



Fig. 11. Effect on HC emission

The incomplete combustion of fuel leads to unburned HCs, which are released because of surplus supply of fuel or insufficient oxygen. Fig. 11 indicates the total HC emissions in the unburned state at the full load of all fuel combinations. B20AC has the minimal HC emissions and B20W has the highest HC emission of all the blended fuels. The HC emissions are minimized, and NPs of $Al_2O_3$ and $CeO_2$ are important because they are used to introduce binders to reduce the unwanted accumulation of fuels and to stop the crevices from penetrating. The high combustion efficiency and energy density of fuel is due to their high $O_2$ content which enhances the combustion process by helping further oxidation of fuel and reduction in the unburned HC emissions [39]. Moreover, the fact that they have a higher surface-volume (S/V) ratio also contributes to the minimized level of HC emissions. On the other hand, the addition of water in the B20 mixture led to increased HCs. The vaporization of water takes in heat energy of the combustion chamber, which decreases the efficiency of combustion and causes less fuel oxidation to happen. Additionally, the occurrence of water enhances the droplet development in the fuel spray which may cause incomplete mixing of the air and fuel in case of its unburning as HC emissions. Nevertheless, on the addition of water and NPs to B20 (B20WAC), the emissions of HC were similar to those of B20. Compared to B20C and B20A, HC emissions fell by 7% and 12% respectively, whereas they rise by 49% using B20W [40].

### 4.7 Carbon monoxide

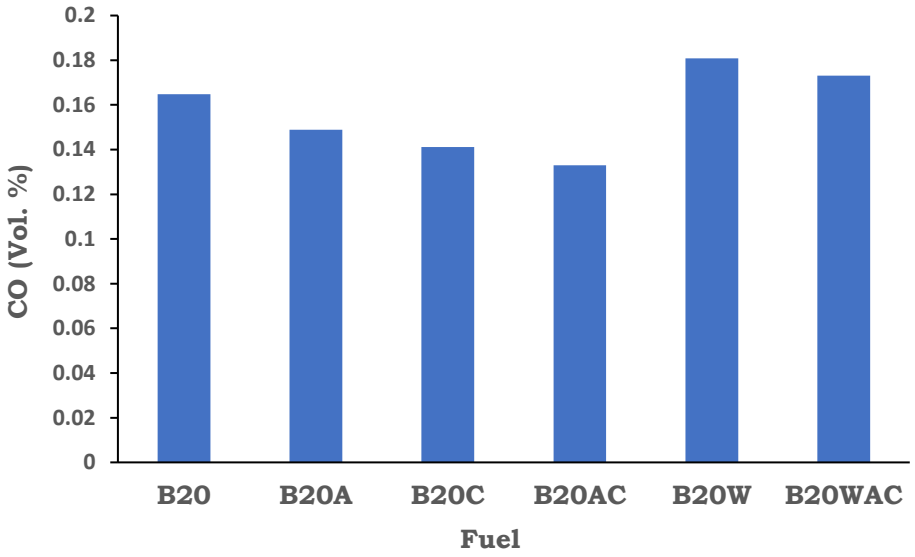



Fig. 12. Effect on CO emission

The incomplete combustion of HCs, CO emissions are caused by the incomplete combustion of fuels. Fig. 12 shows the CO emissions for different fuel blends. The finding indicates that the emission of CO usually reduces with the inclusion of NPs and with the inclusion of water in B20, the CO emission increases. The efficiency of combustion is increased by NPs with its high level of $O_2$ content, high density of energy, and high oxidation properties with stronger complete combustion and reduced CO emissions. However, the opposite is true as when water is added to B20, it suppresses the temperature of local flames because of the large latent heat of vaporization, which reduces the rate of oxidation reactions and increases the formation of CO. It has also been reported that the amount of water content (up to 4 %) may decrease CO emission by 35 %, but at the same time water addition (to biodiesel, 6 %) enhances the CO emission [41]. In the experiment, higher CO emissions were generated by applying 5 % of water content (B20W) in the experiment. In general, the CO emissions were reduced by 14%, 21% and 28% with B20A, B20C and B20AC respectively compared to the B20. Nevertheless, the CO emission with B20W and B20WACgrew by 14 % and 7 % respectively, in comparison to B20. This is mostly because of poor oxidation of CO into $CO_2$, which is a product of lower temperatures in the in-cylinder under the influence of high latent heat of vaporization of water [42].

### 4.8 Carbon dioxide

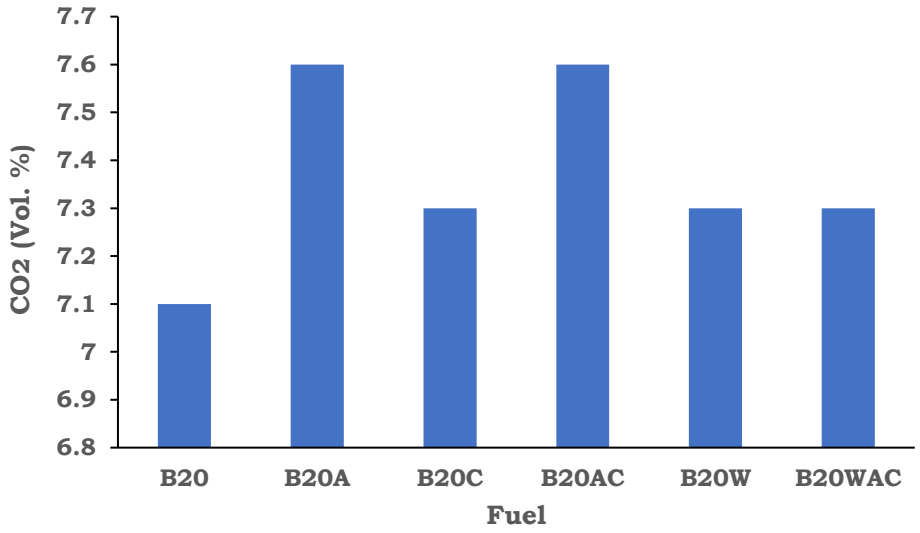



Fig. 13. Effect on $CO_2$ emission

The primary sources of $CO_2$ emissions are the complete combustion of carbon bearing fuels, as an indicator of fuel consumption and combustion efficiency. The maximum $CO_2$ emission is known to happen with B20A, as indicated in Fig. 13, although the presence of $CeO_2$ and water on B20 results in increased $CO_2$ evolution as compared to when B20 is used alone [34]. This higher production of $CO_2$ is attributed to the presence of $O_2$ on $Al_2O_3$ and $CeO_2$ which is responsible for enhanced oxidation and combustion. The $CO_2$ emission in the presence of B20A and B20AC (compared to B20) was increased by 7% but with B20C, B20W and B20WAC it was increased by 3%. Even though an increase in $CO_2$ emission is an indication of increased combustion efficiency, this pattern also indicates the direct proportion between the fuel consumption and $CO_2$ emission. It is resulted by contribution of higher rate of heat release and better ignition performance provided by NPs, which results in more complete combustion and more $CO_2$ emission.

## 5. Conclusions

It significantly increases combustion in biodiesel blends when $Al_2O_3$ and $CeO_2$ nanoparticles are used in combination with water through emulsification. $Al_2O_3$ is a catalyst of ignition and growth in peak pressure that occurs through catalyst radicals, whereas the establishment of $CeO_2$ rises the peak pressure. Their hybrid (B20AC) spins the best pressure phase and, with water emulsification (B20WAC) the highest IMEP. In the heat release, B20A, B20C and B20AC have increased peak HRR. Added water (B20W) improves the atomisation, raising the HRR and reducing the combustion time. The triple-additive mix (B20WAC) performs with cumulative heat release and increase combustion. The findings suggest that a

hybrid solution of nanoparticles and water could enable the maximum possible combustion, energy production and emissions of biodiesel engines. B20A had higher ignition and reduced cut combustion time indicating the high catalytic power of $Al_2O_3$. B20C had a small effect on duration and slight delay in ignition resulting in an improvement in post burning. B20AC hybrid fuel enhanced the ignition timing and shortened time with predominant $Al_2O_3$ effects supported by $CeO_2$. Emulsification on water slowed down the ignition but reduced the period by a quarter because of better atomization. The B20WAC mixture recorded the highest ignition and the shortest lifetime indicating the existence of a high level of synergy. The lowest ITE was present in the B20 blend, whereas the addition of $Al_2O_3$ nanoparticles raised ITE, probably because it enhanced heat transfer and catalytic oxidation, whereas $CeO_2$ did not have as significant an effect, probably being associated with ignition lag-time and unspent energy. Additional improvements were not significant with the combination of $Al_2O_3$ and $CeO_2$, which indicated that $Al_2O_3$ took the upper hand. ITE was significantly enhanced by water emulsification which led to improved atomization and heat losses were reduced by the effect of micro-explosion. The ITE maximised in the B20WAC blend was in the presence of water emulsification and nanoparticles wherein the responding factors of combustion kinetics and cooling forces were balanced to achieve maximum efficiency. $Al_2O_3$ and $CeO_2$ nanoparticles improved combustion efficiency by reducing HC and CO emissions, with a slight increase in NOx and $CO_2$. B20A increased NOx, while B20C and B20AC reduced it, respectively, similar to B20W. The combined blend (B20WAC) showed the most significant NOx reduction). HC emissions decrease with B20A, B20C, and B20AC but increase with B20W due to water-induced quenching. CO emissions dropped with nanoparticles, but increased with water and B20WAC. $CO_2$ emissions increased for B20A, B20AC, B20C, B20W and B20WAC due to enhanced oxidation. In conclusion, the results suggest that the addition of water and nanoparticles to biodiesel blends is a potential approach to improving engine performance, thermal efficiency, and emissions of a diesel engine.

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**Data Availability Statement**

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.