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Article

Optimization of combustion characteristics on a diesel engine fueled by Mahua biodiesel with dispersion of graphene oxide and zinc oxide nanoparticles as additives using design of experiment

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Abstract: The current research investigates the effects of adding metallic graphene oxide (GO) and non-metallic zinc oxide (ZnO) nanoparticles to Mahua biodiesel blend (B20) on the combustion parameters of a diesel engine. GO and ZnO nanoparticles were utilized at a concentration of 75 mg/L, combined with a 1:1 mixture of the surfactant CTAB and the dispersant TWEEN 80. When nanoparticles were introduced to blended biofuel, combustion parameters such as cumulative heat rate, mean gas temperature, mass percent burnt, and rate of pressure rise (RoPR) greatly improved at higher injection pressures. When compared to clean diesel, utilizing B20+ZnO Nanoparticles+ NIS dispersant at 250 bar resulted in 6%, 15%, 7%, and 7.6% improvements in Crankcase Heat Release Rate (CHRR), Mean Gas Temperature (MGT), Mass Fraction Burnt (MFB), and RoPR, respectively. The correlation coefficient (R2) for B20+ZnO NPs+ NIS (1:1) for CHRR, MGT, MFB and RoPR is 0.975, 0.978, 0.966 and 0.9883 when compared to GO nanoparticle inclusions, considering it as optimum combination and an efficient fuel. When compared to other fuel samples, the CHRR, MGT, MFB and RoPR for B20+ZnO NPs+ NIS are 2.484%, 3.2%, 2.6% and 1.25% higher, respectively, according to a statistical analysis conducted by design expert.

Nomenclature

B100	100% Mahua biodiesel
B20	20% Mahua biodiesel In diesel
B20+GO NPs	20% Mahua biodiesel in diesel+ Graphene Oxide 75 mg/L nanoparticles
B20+GO NPs+ CS (1:1)	20% Mahua biodiesel in diesel+ Graphene Oxide 75 mg/L nanoparticles + cetyl trimethyl ammonium bromide 75 mg/L dispersant

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B20+GO NPs+ NIS (1:1)	20% Mahua biodiesel in diesel+ Graphene Oxide 75 mg/L nanoparticles + Tween 80 (or) polysorbate 80 dispersant
B20+ZnO NPs	20% Mahua biodiesel in diesel+ Zinc Oxide 75 mg/L nanoparticles
B20+ZnO NPs+ CS (1:1)	20% Mahua biodiesel in diesel+ Zinc Oxide 75 mg/L nanoparticles + cetyl trimethyl ammonium bromide 75 mg/L dispersant
B20+ZnO NPs+ NIS (1:1)	20% Mahua biodiesel in diesel+ Zinc Oxide 75 mg/L nanoparticles+ Tween 80 (or) polysorbate 80 dispersant
Mg/L	Milligram per litre
GO	Graphene oxide
ZnO	Zinc oxide
NaOH	Sodium hydroxide
IP	Injection pressure
CO	Carbon dioxide (%)
UHC	Unburnt hydrocarbons (ppm)
NOx	Carbon Nano Tubes
CNT's	Oxides of nitrogen (ppm)
CeO_2	Cerium Oxide
$FeCl_3$	Ferric Chloride
ASTM	American Society for Testing and Materials
Al_2O_3	Aluminium Oxide

1. Introduction

Biodiesel is acknowledged as an environmentally friendly and sustainable alternative to conventional fuels due to its absence of sulphur and lower emissions of pollutants. The accessibility and effective utilization of energy sources significantly influence a nation's socioeconomic standing [1]. Biodiesel distinguishes itself as a widely embraced sustainable option owing to its biodegradable and renewable characteristics. Among a range of energy conversion technologies, the diesel engine occupies a notable status, thanks to its outstanding features, include high compression ratio, excellent thermal efficiency, and low specific fuel consumption, the capacity to employ leaner air-fuel mixtures, dependability, and cost-efficiency. These attributes render diesel engines invaluable across diverse sectors, including electricity generation, automotive transportation, agricultural machinery, rail transport, and marine vessels [2, 3]. Various studies have explored the use of different vegetable oils, such as palm, soybean, cashew nut, Jatropha, neem oil, and castor as fuels in diesel engines [4]. XRD and SEM were used to analyse electrochemically generated copper nanoparticles. Copper NPs with an average size of 30 nm were confirmed by XRD and SEM. Nano-additives optimize mean gas temperature and CHRR and lowered specific fuel consumption relative to biodiesel blends, but not as much as pure diesel fuel. An enhanced combustion chamber oxidation reaction increased heat release and combustion characteristics [5]. Additionally, hazardous pollutants such carbon monoxide (CO) and hydrocarbons (HC) are produced by diesel engines [6]. Nano additions have a considerable impact on the characteristics of fuel, improving combustion and lowering exhaust emissions [7]. Copper, iron, cobalt and cerium metal oxides have all been introduced as additives to biodiesel as additives with the goal of enhancing combustion kinetics [8, 9]. As catalysts, nanoparticles have benefits over conventional fuels, including shorter ignition delays, better energy densities, improved combustion and reduced emissions [10]. Therefore, in order to increase engine combustion characteristics and minimise emissions, researchers have investigated biodiesel combined with nanoparticles [11–13]. There have been initiatives to improve the viability and efficiency of neat biodiesel, according to the literature. In this work, GO and ZnO nanoparticles in biodiesel at a ratio of 75 mg/L are examined for their effects. These additives' effects are contrasted with those of diesel fuel and plain biodiesel [14–16]. According to the literature, efforts have been made to increase the viability and effectiveness of clean biodiesel production. In this study, mahua oil was utilised to make biodiesel, and a compression ignition engine was used to analyse the fuel's characteristics. Additionally, the effects of adding a nano-additive were investigated. Using GO and ZnO nanoparticles at 75 mg/L, the study examined the impact of additives on combustion based on prior research. The graphene oxide and zinc oxide addition results were then compared to those of regular diesel fuel and pure mahua biodiesel.

2. Materials and methodology

2.1. Biodiesel production

The first step is pure esterification rather than transesterification. Transesterification occurs after esterification, but it is slower in acid than in caustic circumstances, and because the conversion process is considerably more equilibrium sensitive, it will not convert complete oil into methyl ester. In the first step, it combines an acid and an alcohol to produce a compound. The alcohol is still methanol, but the catalyst in this method is sulfuric acid rather than sodium hydroxide. One of the regular ingredients must be sulfuric acid that is at least 95% pure. The amount, quality, and kind of catalyst employed, as well as the reaction duration, and stirring speed, and temperature maintained throughout the transesterification process,

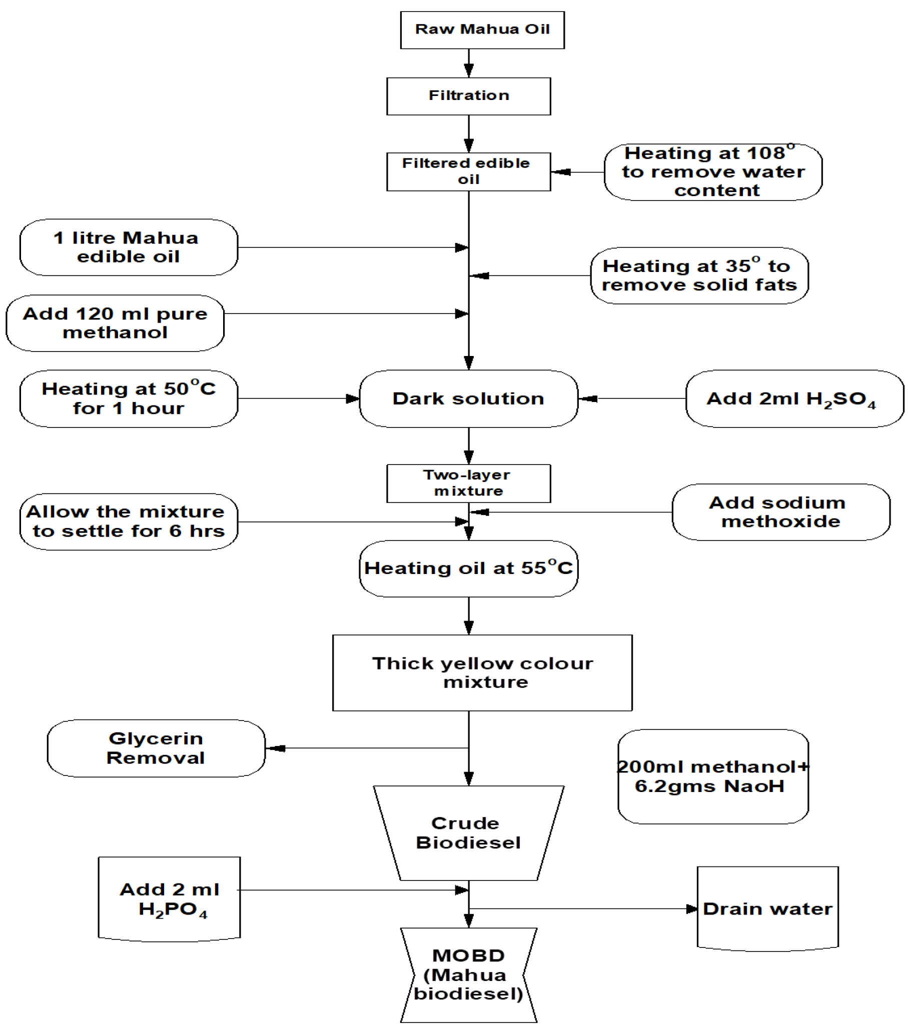

Figure 1. An illustration of biodiesel production using two stage transesterifications.

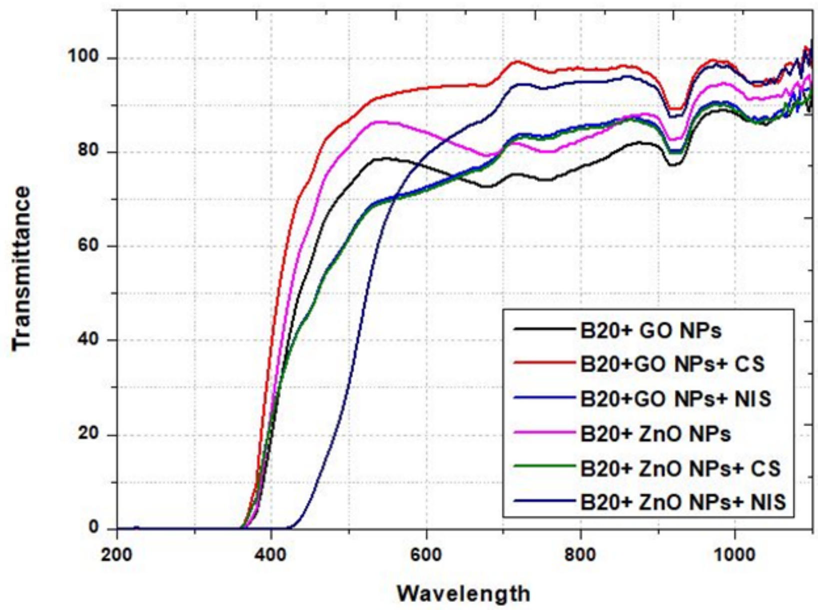

Figure 2. Stability test analysis.

all influence the percentage of biodiesel output. During the second step of the process, the sulphate ion from sulfuric acid interacts with the sodium ion in the solution to generate sodium sulphate, a water-soluble salt that is removed in the water wash. Figure 1 depicts the step-by-step biodiesel production process and its flow chart.

2.2. Nanofuel preparation

Pure GO and ZnO nanoparticles were mixed together in a 1:1 ratio with CTAB and TWEEN 80, then subjected to a 30-minute sonication procedure [17]. The resulting solution was then allowed to air-dry for 8–10 hours. Subsequently, B20 was blended with nanoparticles to produce a variety of nanofuel samples, including B20+GO NPs, B20+GO NPs+CS, B20+GO NPs+NIS, B20+ZnO NPs, B20+ZnO NPs+CS, and B20+ZnO NPs+NIS.

2.3. Stability test analysis

A UV spectrophotometer was used to conduct a spectral transmission analysis to examine the stability of the fuel sample over the course of 10 days. Throughout the ten-day testing period, the fuel mix maintained its stability since all the samples' transmittance values were consistently identical across a range of wavelengths. Notably, this constant transmittance persisted throughout the ten-day stability test. Light transmittance varied across the six test fuel samples that included metal and non-metal oxide nanoparticles [18, 19]. This disparity suggests that, as shown in Figure 2, Compared to the other samples, the fuel mix's dispersion and stability were improved by the inclusion of metal oxide nanoparticles. To ascertain whether nanoparticles had such an impact, the physicochemical characteristics of the fuel were examined in Table 1 accordance with ASTM standards.

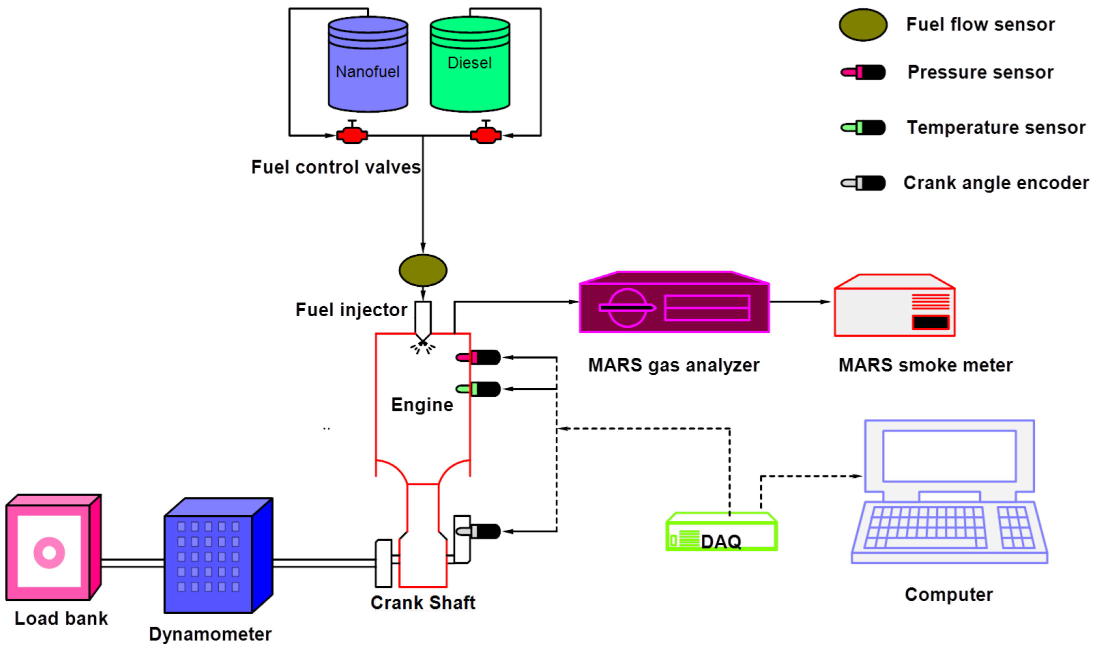

Figure 3. Diagram of a diesel engine testing rig.

Table 1. Physicochemical properties

Properties	Units	Mahua oil	Diesel
Kinematic Viscosity	cSt @ 40 °C	23.76	2.55
Iodine Value	g of I_2/100 g	71.00	-
Density	kg/m^3 @ 20 °C	920.37	829.00
Cloud Point	°C	13	-3.00
Pour Point	°C	9	-8.00
Fire Point	°C	241.69	77.00
Flash Point	°C	233.77	64.00
Acid Value	mg KOH/g	33.00	0.20

3. Experimental setup

In this experiment, a single-cylinder, four-stroke diesel engine, direct injection is used. Table 2 contains the engine's technical specifications. While Figure 3 illustrates the experimental setup. The engine fuel tank can be filled with either diesel or nanofuel for testing purposes [17–19]. To measure emissions, engine exhaust gases were monitored using specialized tools such as gas analyzers and smoke meters. Additionally, engine pressure and crank angle sensors were connected to a computer via an analog-to-digital converter (ADC). The time required for fuel depletion was used to calculate various parameters.

To stabilize the engine, diesel fuel was used for 15 minutes at idle before the test. During testing, loads from 3 to 12 kgf were applied at 1500 rpm. Regular diesel fuel was used first, then BD20 and nano fuels. 200, 225, and 250 bar injection pressures were used throughout the experiment.

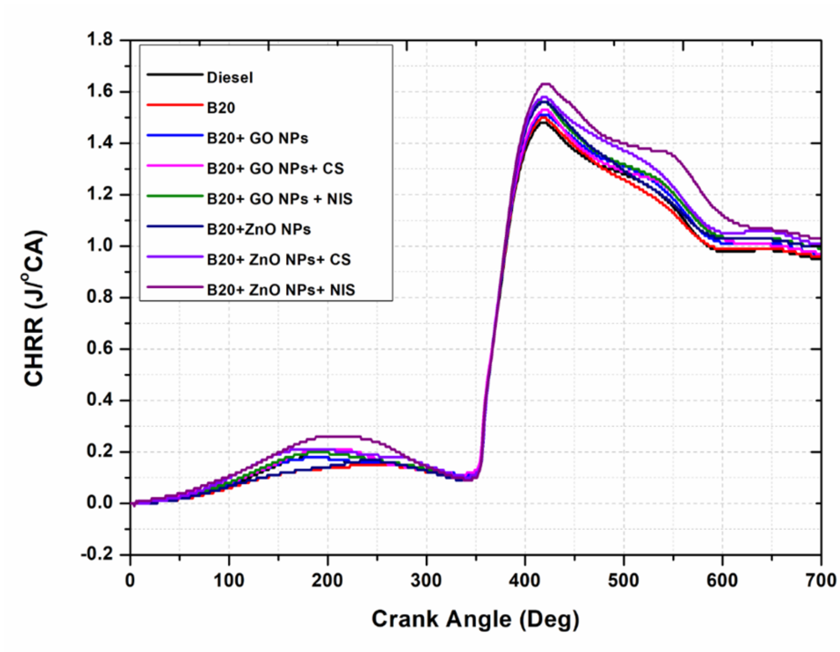

Figure 4. CHRR Vs Crank angle for GO and ZnO nanoparticles inclusions of B20 biodiesel.

Table 2. Specifications of the test set up.

Parameter	Description
Engine make	TAF-1, Kirloskar,
BP (kW)	3.5
Cylinders	1
Bore/Stroke in mm	87.5/110
Compression ratio	17.5
Injection pressure (bar)	200, 225, and 250
Load (kgf)	12
Rotational speed (rpm)	1500

4. Results and discussions

4.1. Combustion characteristics

4.1.1. Crankcase Heat Release Rate (CHRR)

During this ignition delay, the heat release rate is somewhat reduced because injected gasoline absorbs heat from the cylinder. Due to the rapid burning of gasoline combined with air, premixed combustion occurs in this phase. Subsequently, most of the fuel is consumed in a slower and controlled combustion process. Naturally aspirated engines undergo a sequence of premixed fuel burning, followed by diffusion combustion, in all fuel mixtures. The data displayed in Figure 4 shows the total heat release for all fuel samples when the engine is running at a constant load. These images demonstrate the biodiesel mixes' early heat release. When compared to diesel fuel, biodiesel blends may have a lower cumulative heat release due to their lower calorific value. Experimental findings indicate that Diesel, B20, B20+GO NPs, B20+GO NPs+ CS, B20+GO NPs+ NIS, B20+ZnO NPs, B20+ZnO NPs+ CS, and B20+ZnO NPs+ NIS exhibit

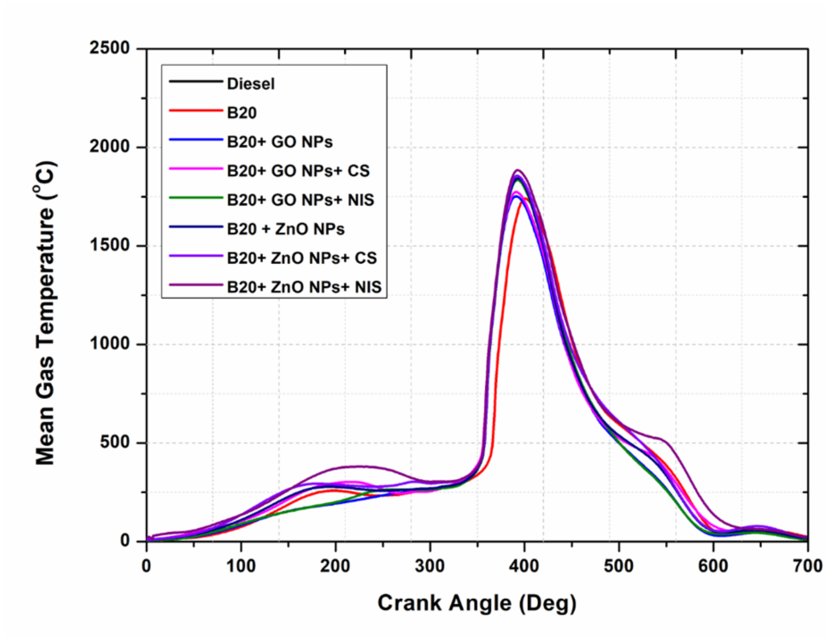

Figure 5. MGT Vs Crank angle for GO and ZnO nanoparticles inclusions of B20 biodiesel.

similar combustion behaviour, with B20+ZnO NPs+ NIS igniting a little earlier than diesel because it has a shorter ignition delay and a longer combustion duration. Biodiesel containing GO and ZnO nanoparticles emits less heat during premixed combustion than diesel fuel. Diesel fuel experiences a longer delay and a higher maximum combustion rate during premixed combustion.

4.1.2. Mean Gas Temperature (MGT)

The graph in Figure 5 depicts the fluctuation in crank angle with mean combustion gas temperature under full load conditions in a diesel engine using various nanofuel combinations. When compared to utilising diesel alone, the MGT increased as a result of the addition of nanoparticles to fuel. This increase can be attributed to the catalytic effects of GO and ZnO, both metallic and non-metallic oxides. The combustion process is improved by these effects, increasing the mean combustion gas temperature. Notably, the combination of B20 with ZnO and NIS at 1:1 ratio demonstrated a more significant increase in mean combustion gas temperature compared to other fuel samples. The higher heat of vaporisation shown in the other fuel samples, which tends to reduce the in-cylinder temperature, may be to blame for this temperature increase [20]. Additionally, the use of nanoparticles significantly advances ignition, which enhances the spray properties of diesel during combustion. In summary, the inclusion of GO and ZnO nanoparticles in diesel has resulted in a 15% higher peak combustion gas temperature at full load conditions.

4.1.3. Mass Fraction Burned (MFB)

Figure 6 below illustrates the mass fraction burned for various tested fuels at different crank angles, including B20+GO NPs, B20+GO NPs+ CS, B20+GO NPs+ NIS, B20+ZnO NPs, B20+ZnO NPs+ CS, and B20+ZnO NPs+ NIS. According to the graph, all the tested fuels exhibit a similar pattern in mass fraction burned at full load. For instance, the mass fraction burned curve for the B20+ZnO NPs+ NIS mix is steeper, indicating a quicker combustion time. Furthermore, the B20+ZnO NPs+ NIS blend burns through the 80% mass fraction faster than the other fuels. This can be due to the previously described reduced ignition delay, which allows combustion to begin slightly earlier than with the other studied fuels. Although

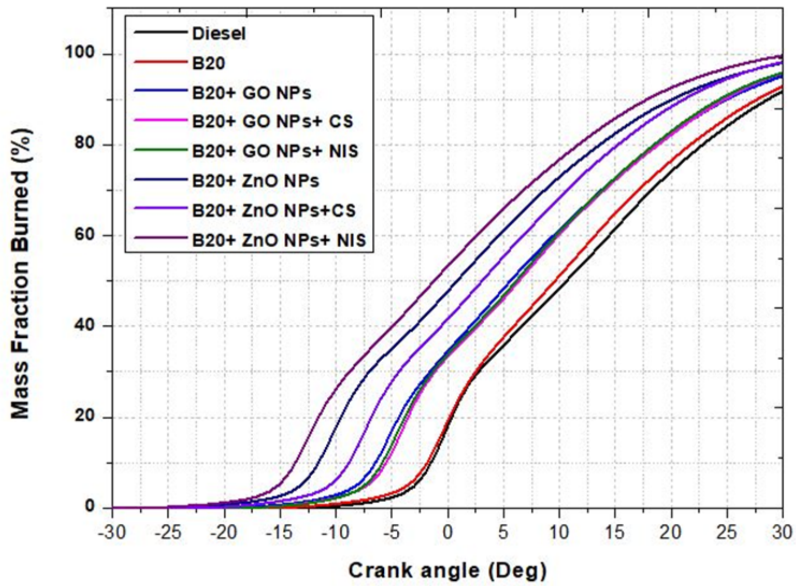

Figure 6. MFB Vs Crank angle for GO and ZnO nanoparticles inclusions of B20 biodiesel.

all fuel samples initiate combustion at nearly the same crank angle of 8°ATDC (After Top Dead Centre), there is some variance in the time of combustion initiation among them as shown in Table 3. In comparison to the comparable baseline diesel, the combustion duration is reduced by an average of 1.475°CA (Crank Angle) in the B20+ZnO NPs+ NIS blend. As a result of the rapid energy release, the engine loses less heat since there is less time for the heat to pass from the cylinder to the coolant and dissipate.

Table 3. Mass Fraction Burnt (%) at different crank angle.

Fuel	MFB 20%	MFB 40%	MFB 60%	MFB 80%	MFB 100%
Diesel	0.32°CA	6.25°CA	14.78°CA	22.5°CA	33.1°CA
B20	0.36°CA	6.21°CA	14.88°CA	22.6°CA	32.7°CA
B20+GO NPs	-4.21°CA	2.5°CA	9.8°CA	17.8°CA	32.15°CA
B20+GO NPs+CS	-3.7°CA	2.5°CA	9.9°CA	18.75°CA	31.2°CA
B20+GO NPs+NIS	-3.8°CA	2.5°CA	10°CA	18.3°CA	31.1°CA
B20+ZnO NPs	-9.2°CA	-2.5°CA	5°CA	13.1°CA	30°CA
B20+ZnO NPs+CS	-7.1°CA	-2.1°CA	6.3°CA	15°CA	29.8°CA
B20+ZnO NPs+NIS	-11.1°CA	-5°CA	2.5°CA	11.8°CA	30°CA

4.1.4. Rate of Pressure Rise (RoPR)

The peak pressure within the engine cylinder is the highest-pressure point during the initial rising phase of the engine cycle and exceeds the pressure generated by combustion. This pressure fluctuates as the crankshaft angle varies throughout the engine's operating cycle, reaching its peak near the top dead center, which contributes to improved engine performance [21,22]. The fluctuation in RoPR for a mahua biodiesel mix under various engine load situations is shown in the Figure 7 below for various fuel samples. At full load B20+GO NPs+ CS (1:1) and B20+ZnO NPs+ NIS have shown improvement in RoPR in elevated compressed air pressure and engine temperature. It contributes to stability while maintaining the desired

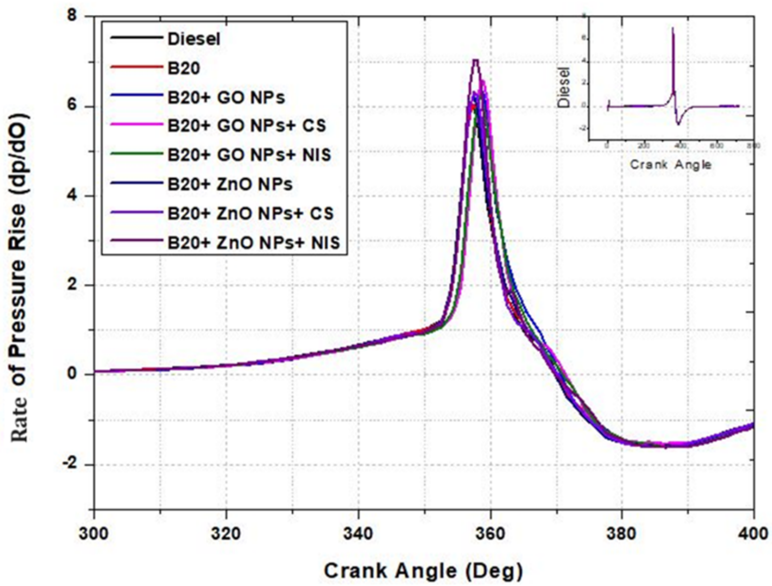

Figure 7. RoPR Vs Crank angle for GO and ZnO nanoparticles inclusions of B20 biodiesel.

temperature levels, with a smaller volume of air and pressure. The Maximum Rate of Pressure Increase is crucial for all engine loads, as indicated in Figure 7, and is a key characteristic of the tested gasoline blends. The use of biodiesel leads to lower peak pressure levels, which decrease noticeably as the blend ratio increases or varies. Additionally, a significant reduction in heat release was observed across the study.

5. Design-Expert Software performs statistical analysis on experimental data

Design Expert is critical in the analysis of complex datasets generated during biodiesel research. Design Expert's powerful statistical tools enable users to identify key elements, relationships, and trends in data, allowing for a more in-depth understanding of biofuel characteristics. This information is crucial for optimizing combustion and emission parameters and assuring consistent and reliable results.

5.1. Combustion characteristics using design expert

Figures 8, 9, 10 and 11 illustrate the prediction and the experimental findings related to CHRR, MGT, MFB and RoPR for GO and ZnO nanoparticles inclusions, respectively. Also presented are the outcomes of the experiments. It turned out to be plainly evident that the CHRR, MGT, MFB and RoPR models' forecasts employing the design expert had showed an exceptional outcome. The results for the correlation coefficient, R2, were as follows: 0.968 and 0.975 for CHRR with GO and ZnO nanoparticles inclusions; 0.971 and 0.978 for MGT with GO and ZnO nanoparticles inclusions; 0.991 and 0.985 for MFB with GO and ZnO nanoparticles inclusion; and 0.986 and 0.9883 for predicted and actual RoPR .

5.1.1. Mean Gas Temperature (MGT)

To better comprehend the relationship between the factors and the response, a 3D surface plot was made. The surface plot of the connection between injection pressure and load regarding CHRR is shown in the Figure 12 (a)-(b), because biodiesel has a lower heating value than diesel fuel, the CHRR from the engine for biodiesel is lower. When oxide nanoparticles are taken into account, a significant increase in heat release rate is shown. As a result, 2.484% more heat was released by B20+ZnO NPs+ NIS than by various inclusions of graphene oxide nanoparticles, suggesting that it may replace diesel fuel.

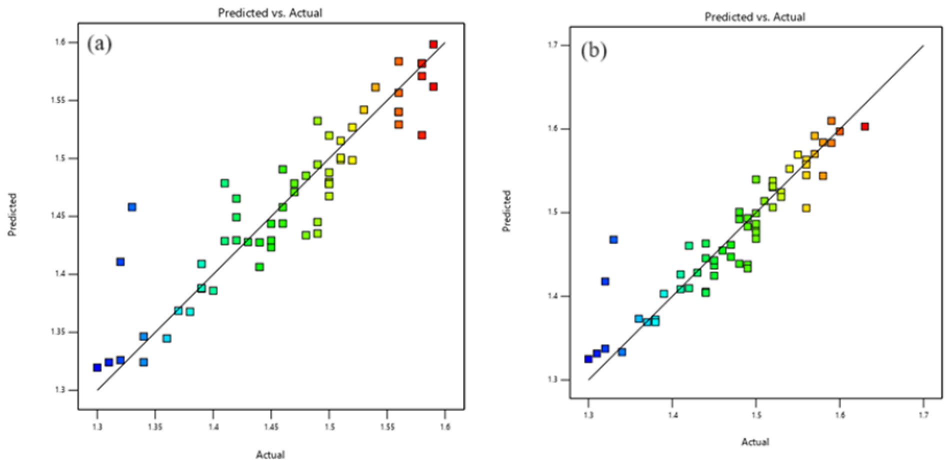

Figure 8. Predicted Vs actual CHRR for GO and ZnO nanoparticles inclusion in B20.

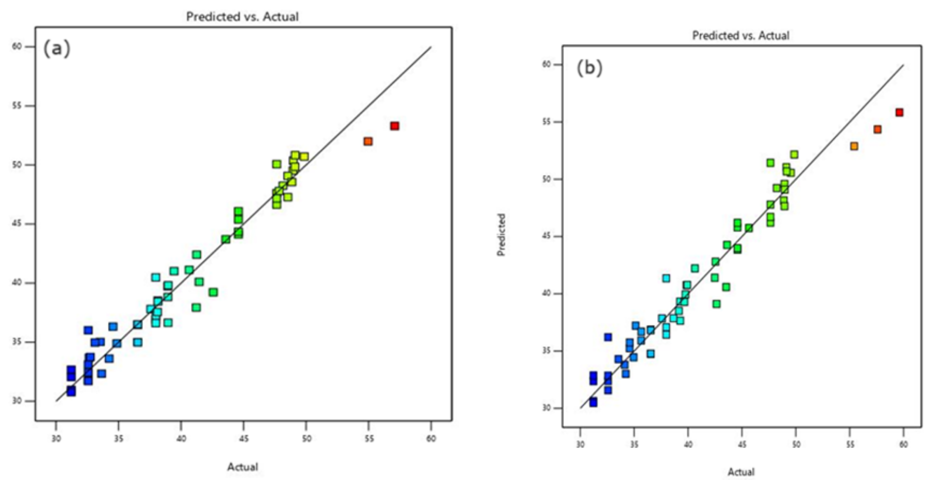

Figure 9. Predicted Vs actual MGT for GO and ZnO nanoparticles inclusion in B20.

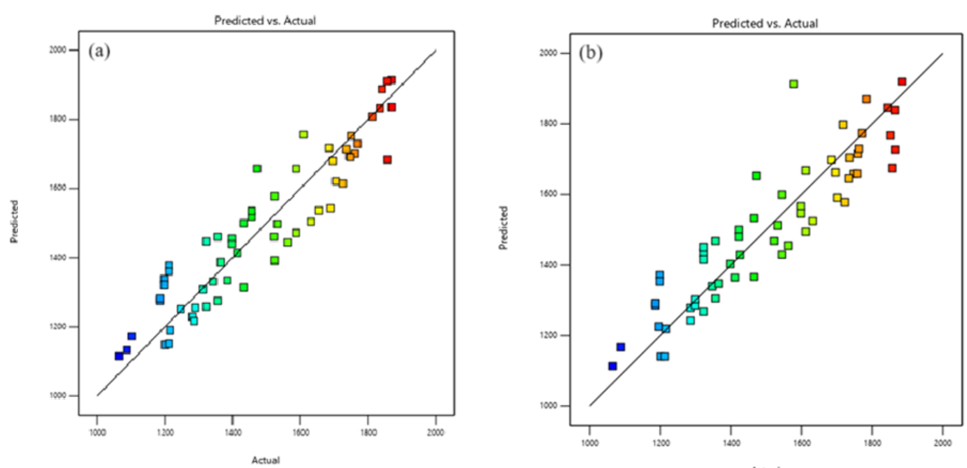

Figure 10. Predicted Vs actual MFB for GO and ZnO nanoparticles inclusion in B20.

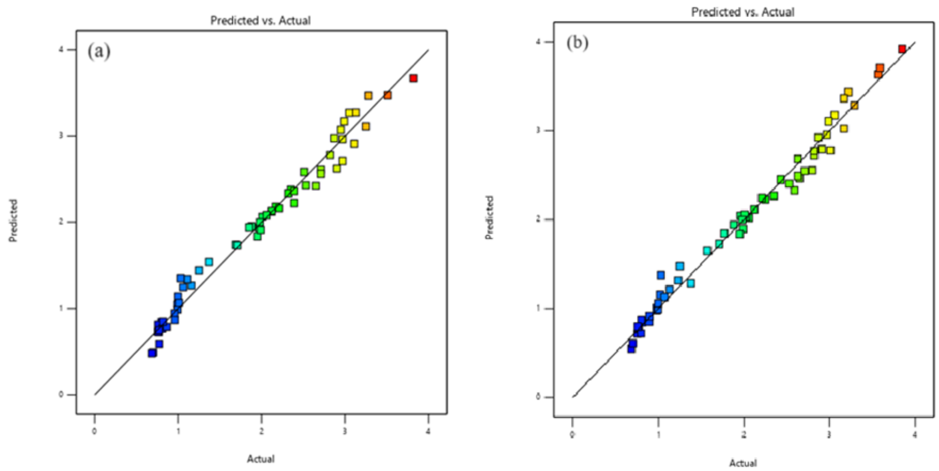

Figure 11. Predicted Vs actual RoPR for GO and ZnO nanoparticles inclusion in B20.

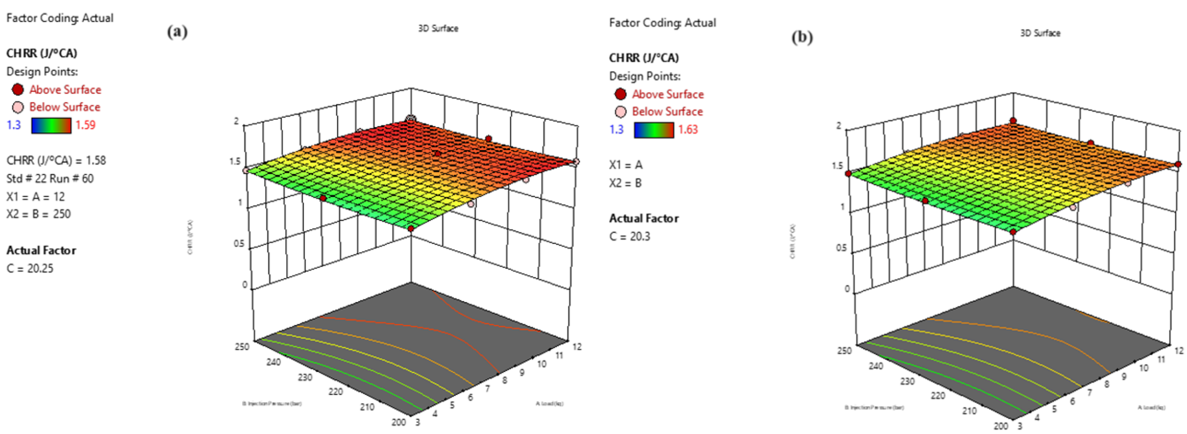

Figure 12. 3D Plot for CHRR of GO and ZnO nanoparticles included B20.

5.1.2. Mean Gas Temperature (MGT)

The surface plot of the connection between the injection pressure and load as it relates to the mean gas temperature for MOBD with inclusion of GO and ZnO nanoparticles is shown in Figure 13 (a)-(b). Compared to other fuel samples, the improved combustion rates of B20+ZnO NPs+ NIS led to an increase in exhaust gas temperatures that was 3.2% higher, which led to greater brake thermal efficiencies when compared to other fuel samples.

5.1.3. Mass Fraction Burnt (MFB)

Figure 14(a)–(b) displays the surface plot for the relationship between crank angle and mass fraction burnt for mahua biodiesel blends included with GO and ZnO nanoparticles. The mass fraction burnt (MFB) courses for each blended mixture under analysis are shown in the figures below. Compared to diesel, the other fuel blends have a lower cetane number and higher heat of vaporization. The mass fraction burned (MFB) represents the percentage of fuel consumed over time during combustion. Biodiesel with oxide nanoparticles shows a 1.5% performance increase compared to diesel and B20. The presence of GO and ZnO oxides in biodiesel blends has significantly improved other performance parameters by enabling proper and efficient fuel combustion.

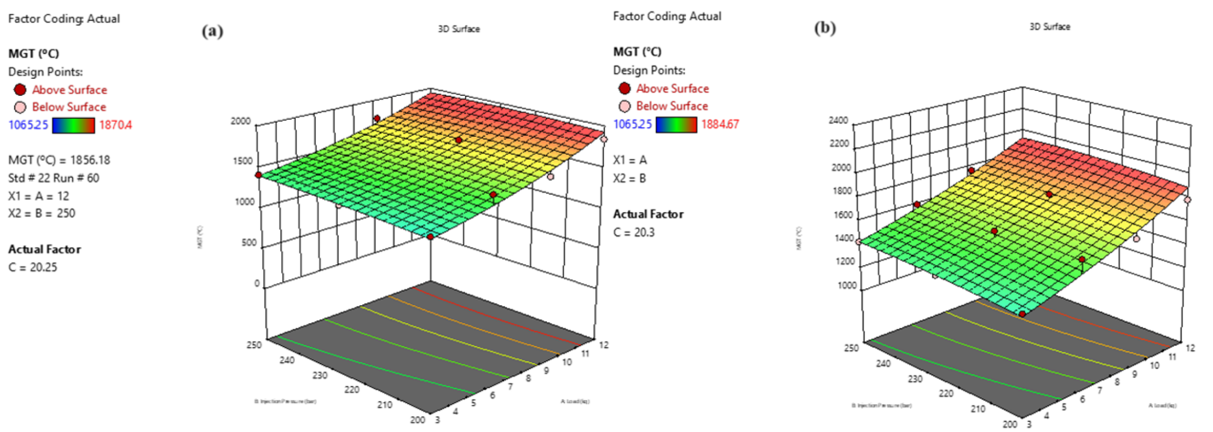

Figure 13. 3D Plot for MGT of GO and ZnO nanoparticles included B20.

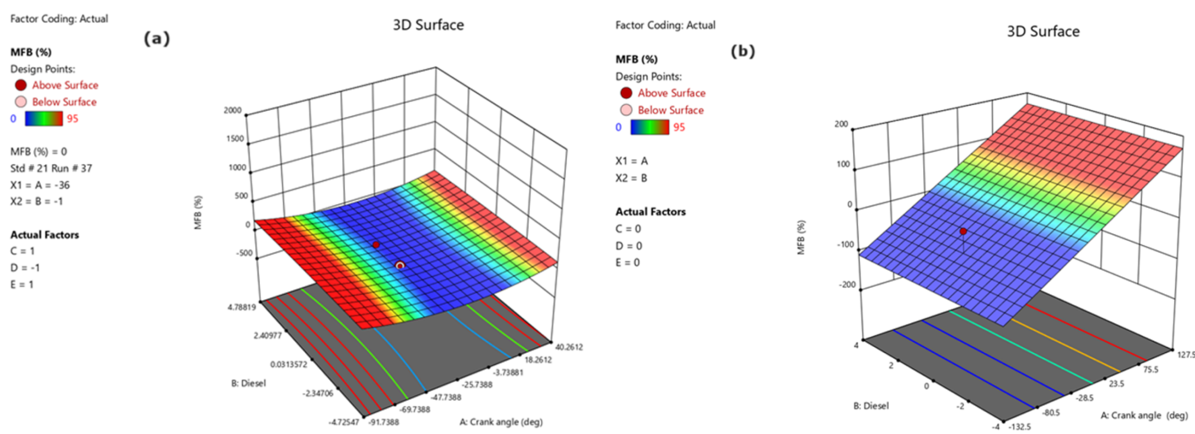

Figure 14. 3D Plot for MFB of GO and ZnO nanoparticles included B20.

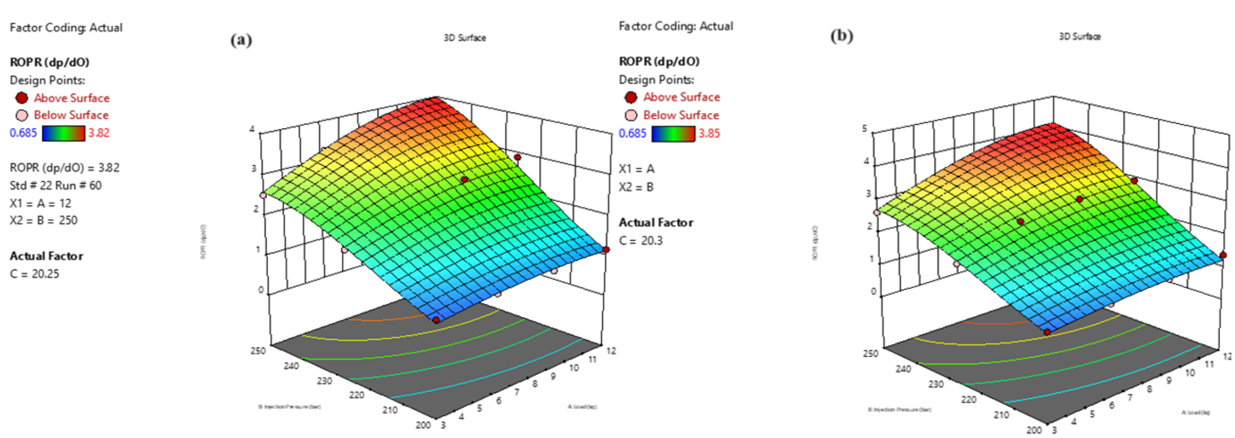

Figure 15. 3D Plot for RoPR of GO and ZnO nanoparticles included B20.

5.1.4. Rate of Pressure Rise (RoPR)

Rate of pressure rise of Diesel, B20, B20+GO NPs, B20+GO NPs+ CS, B20+ZnO NPs, B20+ZnO NPs+ CS, and B20+ZnO NPs+ NIS with the engine running at 1500 rpm and at full load are shown in the Figure 15 (a)-(b). Diesel fuel has a peak pressure rise of 2.28 bar/deg, and B20+ZnO NPs+ NIS has a peak pressure rise of 2.05 bar/deg. Diesel fuel has a higher peak pressure during combustion because the spark delay causes combustion to start before the TDC. This means that heat is released quickly during premixed combustion. As the nanoparticles are premixed before combustion for blended biodiesel , B20+ZnO NPs+ NIS exhibited maximum pressure rise allowing the fuel to reach to its peak pressure and combust the whole fuel.

6. Conclusions

Upon completion of the study, the following conclusions were investigated:

- Using TWEEN 80 and CTAB to disperse the GO and ZnO nanoparticles in B20 improved their stability. The dispersant had a greater impact on stability than the surfactant.
- After being assessed in accordance with ASTM standards, for evaluation, the physicochemical properties of diesel and mahua oil are taken into account.
- Using B20+ZnO NPs+ NIS dispersant at an injection pressure of 250 bar have shown significant improvement in CHRR, MGT, MFB and RoPR at 6%, 15%, 7% and 7.6% respectively, as compared to clean diesel.
- Correlation coefficient (R2) for B20+ZnO NPs+ NIS for CHRR, MGT, MFB and RoPR is at 0.975, 0.978, 0.966 and 0.9883, which suggest that this is an ideal combination and an efficient fuel when compared to GO nanoparticle inclusions.
- Statistical analysis using design expert has shown that CHRR, MGT, MFB and RoPR for B20+ZnO NPs+ NIS is 2.484%, 3.2%, 1.5% and 1.25% higher when compared with other fuel samples. As a result, the inclusion of nanoparticles in blended biodiesel has clearly had a dramatic effect on the combustion characteristics of a diesel engine. In the near future, these may be deemed superior choices.

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Author contributions: Conceptualization: [Srinivasa Reddy Pala, M V Krishna Mohan]; Methodology: [M.V.Krishna Mohan]; Formal analysis and investigation: [Srinivasa Reddy Pala], [V.V.S.Prasad]; Writing - original draft preparation: [Srinivasa Reddy Pala], [V.V.S.Prasad], [M.Balaji]; Writing - review and editing: [pala srinivasa reddy, M V Krishna Mohan]; Funding acquisition: Not applicable; Resources: Not applicable; Supervision: [pala srinivasa reddy]; All authors have read and approved the manuscript.

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