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Research Article

Investigation on Delonix regina biodiesel blends on diesel engine with 1-butanol-diesel blends to test engine performance, combustion and emission characteristics

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ABSTRACT

The need for automobiles is rapidly increasing all over the world. The biofuel requirement has also increased due to the need to avoid the nonpolluted atmosphere and improve performance. This work, with its innovative use of nonedible Delonox regina blends with limited proportions of butanol alcohols has practical implications for the automotive industry. The novelty of this research lies in the investigation of 1-butanol additives on Delox regina blends with the lowest proportions followed by 5%,12%, and 14% as a best-boosting ignitor. This limited butanol proportions proved that the engine's thermodynamic performance was better when fuelled with Delonox regina blends and subjected to different loads. The results obtained from the Delonox regina blends and diesel in terms of performance, owing to combustion and owing to emissions for every stage, are compared with diesel. Higher thermal efficiency is obtained for the blend D90DR05B05, and the least BSFC is also attained for the blend D90DR05B05 than diesel, But the emissions are very low for the blend DR 100 followed by CO emissions, which is 34.5% superior to diesel. CO_2 emissions are 14.5% decreased for the blend D70DR16B14 than diesel, HC emissions for blend DR100 are less than 42.5%, and NOx emissions for blend DR100 are less than 23.53% compared to diesel.

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INTRODUCTION

The necessity of biofuel generation and utilization in engines is a trending research topic in science and engineering. This causes the thrust to make new research in engines. The one more common interest involved during the research of biofuels is the possibility of emissions reductions, which tend to create enormous benefits such as less emissions compared to standard diesel fuels [1]. Hence, the researchers focused on reducing the emissions by introducing different technologies like exhaust gas recirculation systems; introducing the EGR gives numerous benefits in terms of better brake-specific fuel consumption and better Brake thermal efficiency compared to diesel engine performance [2]. The one more interesting in the field of biofuel research is that various researchers are continuously trying to find innovative solutions to reduce emissions and improve engine performance through the differences in different proportions of blends with the latest additive technologies for enhancing the improvement of engines [3]. Few researchers have tried hydrogen as the best alternative fuel for improving performance, in which oxy-hydrogen is operated in dual mode to enhance the optimal speeds in the engine [4]. The reduced torque and improvised brake power enable the engine to operate safely in dual mode. A slight modification is required to operate the engine with the help of ceramic coatings such as Yitria stabilized zirconium and cerium oxide with definite proportions [5]. Adding these coatings to the engine cylinder and piston arrangements will improve the piston and cylinder's thermal conductivity, improving the engine's life span [6]. Various studies prove that implementing pyrolysis oil blends with Al_2O_3 additives has higher efficiency than TiO_2-operated blends. This study also proved that adding the Al_2O_3 concerned to 70 ppm improves an engine's thermal performance, causing a greater reduction than others compared to [7]. Further investigation with cotton oil doped with 30 ppm CeO_2 gives the maximum thermodynamic performance of the engine leads by 12.2% than diesel, a significant drop in the brake specific fuel consumption by 13.2% than diesel [8]. The more profound study of capollyum-operated biodiesel blends operated by varying compression ratios engines with 18:1 to 22:1 results in achieving the maximum combustion pressures by 11.1% than diesel [9]. The induction of oxygen and hydrogen-based fuels with palm ingredients results in improvised BTE by 12.3%, Reduced BSFC by 14.2% and reduced NOx by 13.2% compared to diesel [10]. Machine learning algorithms and response surface technology techniques were implemented for the pyrolysis oil operated with butanol blends; from the results, it is observed that maximum efficiency is achieved for the Pyrolysis oil blended with minimal percentages of butanol content varying from 5% to 10% respectively. The higher addition of butanol causes rapid engine vibration, which leads to uncontrollable emissions from the tailpipe to the atmosphere [10]. Adding decanol to palm oil gives lower hydrocarbon emissions by 22.2% than diesel because the presence of higher oxygenated contents in the decontrol tends to achieve fewer emissions from hydrogen, and carbon elements tend to create fewer emissions and higher brake thermal performance than diesel [11]. The originality of this work is that the authors purchased the Dolonix Regina blends from the local supplier at Hyderabad Telangana, and the butanol blends were purchased from Aldrich. The different proportions of butanol with Delonox Regina blend such as D90DR05B05, D80DR08B12, D70DR16B14, and DR 100 to evaluate the thermodynamic performance of engine, combustion, and emission reductions, All the results obtained from these blends are compared with diesel blends and obtained results were justified. The advantages of this technique are that Delox regina seeds are plenty available in the coastal regions of Chennai, and the oil extraction from these seeds is very cheap compared to other seeds; 85% of oil can be extracted from 1 kg of seeds; 15% are the residues and the oil extracted from this seeds is very eco-friendly to use in the various fields, the limitations during the mixing of proportions requires ultrasonication machine, during the mixing per proportion requires addition costs of RS 200 per sample. It takes 10 minutes to complete the mixing; an additional manual stirrer process is required after the ultrasonificator. Another limitation of this experiment is that adding more butanol beyond 25% results in vibrations and excess emissions, especially in NOx emissions, Which damage the piston and cylinder more rapidly than diesel fuel. Hence, limited proportions of butanol with Dolonix Regina blends were utilized.The novelty of the research is to investigate 1-butanol additives on Delox regina blends with the lowest proportions. Many researchers have tried butanol in different research works concerned with palm biodiesel, pyrolysis blends, and jatropha blends, but no researchers have tried it on Delox regina blends. The main objective of this study is to introduce the different types of blends extracted from Delox regina seeds mixed with butanol and predict the performance, combustion, and emissions concerned with ASTM standards.

MATERIALS AND METHODS

The technique adopted for cleaning the obtained Delonix regina blends is purified oil. Adding glycerin into the purified oil with methanol gives the best results regarding well-purified blends, which are ready to use. The cleaned Delonix Regina blends are proportionate with the help of butanol, followed by 5%, 12%, and 14%, respectively. Past literature has defined adding higher butanol significantly damages the piston's crown, leading to permanent failure. Hence, in these methods, we deliberately utilize the butanol concerned with light percentages to improve the thermal performance of the engine.

Testing Procedure

Figure 1 represents the actual experimental setup that testing should be done. The limitations and challenges in the experimental setup include implementing the ignition improver additive, such as butanol, with the lowest proportions of delox Regina blends, which is the most significant challenging blend. The limitation is that if the butanol exceeds the limit of 25 ml, it tends to auto-ignite the combustion, which drops the thermal efficiency of the blends.

The engine is cleaned well before 4 hours of the testing is to be done. Any impurities in the engine lead to a drop in its thermal performance. The higher the knock will affect the engine's performance from average to abnormal combustion. Dry and test reports must be taken before the engine is to be tested; these tests give significant ideas to the researchers concerning the uncertainties that occurred during the analysis and ideas to overcome the uncertainties relating to different types of errors (Table 1).

Table 1. Specifications of the engine

SNO	Description	Specifications
1	Ratio (r)	20
2	Radius of crank	92 mm
3	Power	5.21 KW @ 1500 DR100m
4	Injection type	DI
5	Stroke length	240 mm
6	Length (L) & Bore (D)	122 & 92 mm
7	No of strokes	4

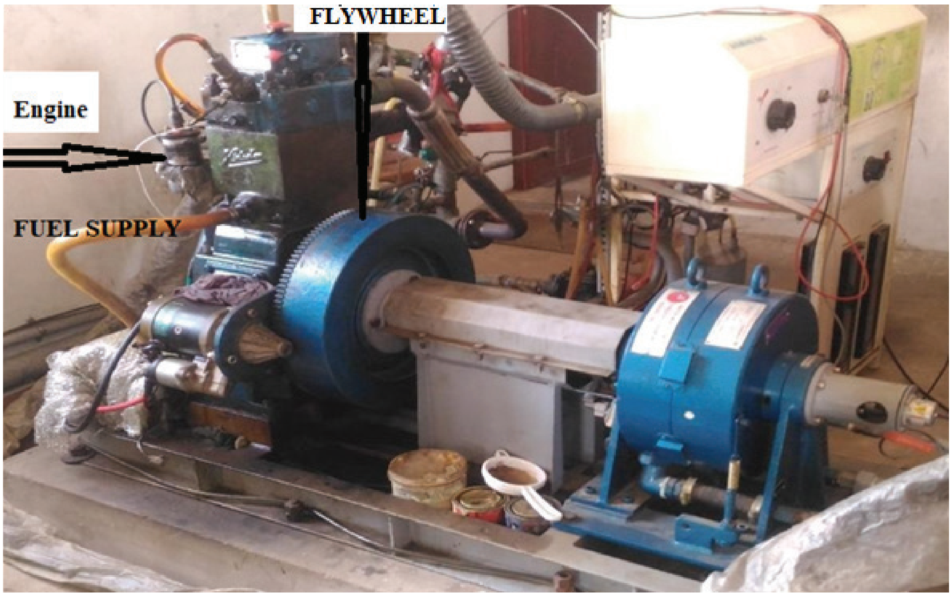

Figure 1. Actual experimental setup.

Table 2. Delox regina-butanol properties

SNO	Properties	ASTM D975	D100	D90DR05B05	D80DR08B12	D70DR16B14	DR100
1	Hydrogen in weight%	14	11	10	9.8	8	4
2	Carbon in weight%	86	77	68	60	50	20
3	Pour point	16-34	12	10	8	6	4
4	Kinematic Viscosity @ 40°C in CST	1.2- 4.2	5	4.06	3.72	2.98	1.87
5	Flashpoint °C	68 - 85	70	65	60	40	30
6	Cetane Number	41 - 60	55	47	46	40	38
7	Cloud point °C	6 - 16	7	6	5	4	2
8	Oxygen in weight%	2%	1.9	1.2	0.9	0.8	0.7
9	sulphur in ppm	600	-	0.8	0.6	0.4	0.2
10	Fire point °C	185 - 345	320	240	200	180	190
11	CalorificValue kj/kg	43021	45021	42012	40012	38012	36782

Table 3. Uncertainties in the experiment

SNO	Used	Parameters	Specifications	Variations	uncertainties (%)
1	Speed Sensor	Speed of the engine	DR100m	±8 DR100m	±0.17%
2	Burette meter	Quality of fuel	0-1200 cc	±0.13 cc ±1.5%	±1.3%
3	Stopwatch	Time in seconds	-	±0.13 s	±0.24%
4	Manometer	Air measurements	0-500mm	±3.1 mm	±1.6%
5	AVL Gas analyzer	HC	0–11000 ppm	±14 ppm	±0.6%
		NOx,	0–5600 ppm	±12 ppm	±0.7%
		CO,	0–14% vol.	±0.05%	±0.7
		CO_2,	0–10% vol.	±0.05%	±0.6

The addition of n-butanol in varying proportions tends to reduce the oxygen content, resulting in poor performance of the blend with higher proportions of n-butanol (Table 2).

Uncertainty Analysis

The most important analysis that predicts the higher accuracy of the experiments and the test results is estimated with the help of uncertainty analysis. The least possible deviations concerning the elementary constitutions evident from calibrated, predicted, and error data could be identified using uncertainty analysis (Table 3).

Equation (1) referred from [12] defines the occurrence of evaluated uncertainties,

$$\sum \Phi_{o=\frac{2\sigma_{\Phi}}{\beta}*100} \tag{1}$$

$2\sigma_{\Phi}$ = Instant errors attained at the experiment

Φ = Theoritical Values that measured.

β = *Repeated Variability*

The measured parameters are expressed from the Eqn (2) as referred to by [13]

$$\boldsymbol{R_s = f(J_1 J_2 J_{3,} \_\_\_\_ J_n)} \tag{2}$$

R_s = Readings that measured.

Eqn (3) demonstrates the measured deviations between performance parameters and uncertainties as referred to by [14]

$$\Delta J = \sqrt{(\frac{\partial j}{\partial j_1}\Delta j_1)^2 + (\frac{\partial j}{\partial j_2}\Delta x_2)^2 + (\frac{\partial j}{\partial j_3}\Delta j_3)^2 + \cdots (\frac{\partial j}{\partial j_n}\Delta j_n)^2} \tag{3}$$

$\frac{\partial j}{\partial j_1}$ = Accuracy of the uncertainty.

RESULTS AND DISCUSSION

BTE

BTE is the heat-liberated amount of power and is scientifically called brake thermal efficiency [15]. In other words, Brake thermal efficiency significantly represents the attainment of power, neglecting the losses from thermodynamic heat engines due to the liberation of chemical energy transformations [16]. The brake thermal efficiency is found by the Equation referred to by [17, 18] through Equation (4) and Equation (5)

$$\eta_{Brake} = \frac{Obtained\ Brake\ Power}{Required\ Fuel\ Power} \tag{4}$$

$$Brake\ \text{power.} = \frac{2 \times \pi \times N \times T_{crank}}{60} \tag{5}$$

Figure 2 represents the attainment of brake thermal efficiency in terms of load conditions. At Optimal loads (100% Load), Brake thermal efficiency is better at optimal loads (100% Load), followed by 32% for diesel. However, Brake thermal efficiency is best for blend D90DR05B05, followed by 31%. The best calorific values attained for the D90DR05B05 with reduced viscosity offer the higher Brake thermal efficiency for the D90DR05B05 blends [19]. The adequate mixing of these blends with limited percentages of

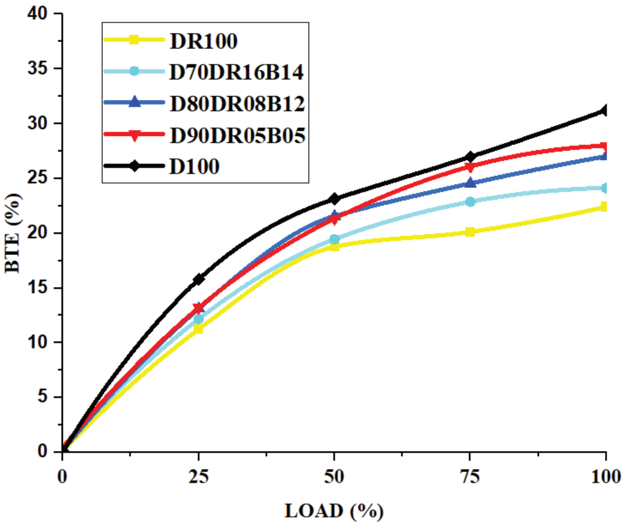

Figure 2. BTE.

butanol requires the optimal mixing of oxygen with detox blends, causing the proper combustion to achieve higher brake thermal efficiencies [20, 21].

BSFC

This term, BSFC, evaluates the mileage consumption of the blends at different speeds. The term BTE is inversely proportional to BSFC. This understanding explains how thermal efficiency increases mileage decreases per kilowatt hour. Consuming less fuel at elevated speeds represents the physical significance of BSFC. Referring from Equation (6), proved by [22]

$$BSFC = \frac{Consumption\ of\ fuel\ at\ various\ loads}{Actual\ power\ developed\ in\ engine} \quad (6)$$

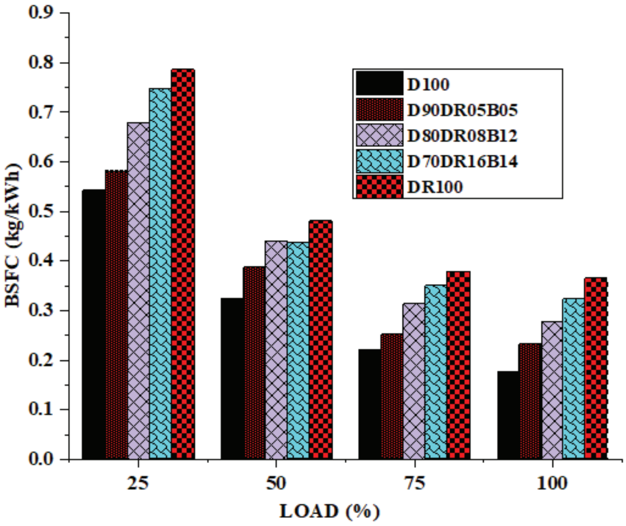

Figure 3. Specific fuel consumption vs. load.

Figure 3 represents the factors that affect the consumption of the blends owing to the different loads. Among the various loads, the peak loads give the physical meaning that scientifically proved the most minor consumption of blends. It is also noted from the figure that at 100% loads, diesel fuel has the most minor consumption, ranging from 0.19 kg/kWh.The inferior blend is D90R05B05, consuming 0.20 kg/kWh, 5.26% higher than diesel. This is the best blend among different blends, owing to the different physical properties evaluated for various blends [23]. D90R05B05 blend possesses the best among others because of the less viscosity offered by this blend and its good heating values, which accelerates the blend at various ratios to attain optimal consumption. Another reason for acheiving the lowest BSFC for blend D90R05B05 is adding the butanol content with limited proportions causes the cylinder pressures to be very high to achieve the optimal consumption of the blends; adding much more butanol than 5% results in decelerating

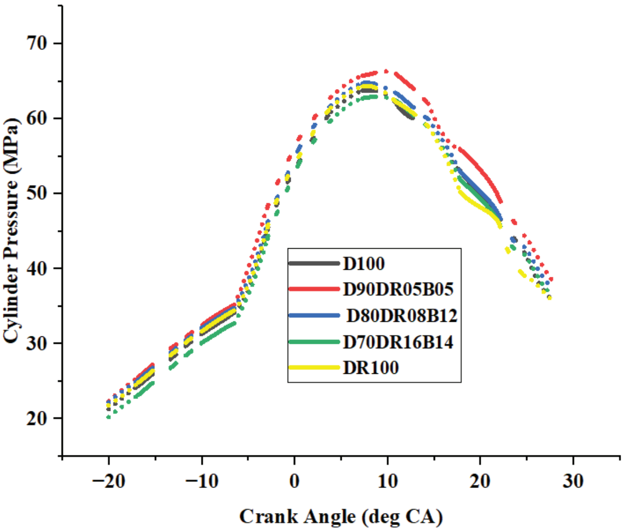

Figure 4. Cylinder pressures.

the blend with reduced calorific values tends the slightest pressure rises in the cylinder [24, 25].

Combustion Characteristics

Cylinder pressures

The attainment of pressure rises in the cylinder from acceleration and deceleration, causing the piston and cylinder rapid transformation to rise or change in pressures, which is predicted using the term cylinder pressures. The critical factors that affect the pressure rising inside the cylinder are ignition delay, ignition timing, and the nature of the movement of crank rotations [26]. The faster the rotations of the crank tend to achieve, the higher the release of heat, resulting in a heavy pressure rise in the cylinder [27]. Figure 4 demonstrates the increase in pressure in the cylinder. The pressure rise is found for the blend D90DR05B05 at the rate of 68 bar. The result of butanal as the igniting alcohol with definite proportions leads to the combustion of the ignition properly compared to diesel. Increasing the butanol content from 5% to 12% and decreasing the cetane number of the blend D80DR08B12 causes a higher ignition delay and results in the lowest pressure inside the cylinder, ranging from 65 bar. The decrease in pressure rise ranged from 23.8% for the blend D80DR08B12 to D90DR05B05 because the D90DR05B05 blend possesses better cetane number and better kinematic viscosity than D80DR08B12 and diesel D100 [28, 29].

HRR

The amount of heat required to attain or the rate at which ignition starts is measured by HRR. The enthalpy of heat formation owing to different crank angle rotations per unit time when the piston travels between BDC and TDC is estimated by HRR. The rise in pressures at elevated temperatures causes the piston and cylinder

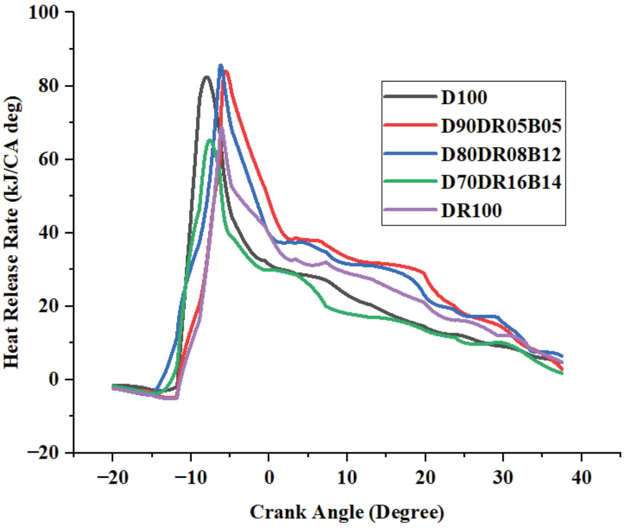

Figure 5. Heat release rate.

transformations through rotation of crank angles, resulting in the production of heat measured by KJ/CA deg [30, 31]. This finite volume of heat transformation through a convective medium results in the transformation of Energy in this process, which results in heat release rates. Figure 5 shows that the maximum heat release rate is achieved for the blends D80DR08B12 and D90DR05B05, followed by 85 kJ/CA degree and 83 KJ/CA degree. The finite difference in HRR obtained for the D80DR08B12 blends is inferior to D90DR05B05 in terms of a 14.92% superior blend. This is because the majority of oxygenated compounds present in the D80DR08B12 blends have the higher acceleration to catch the ignition very quickly than other blends, resulting in better HRR than diesel for the blend D80DR08B12. This results in better attainment of HRR for D80DR08B12 blends than diesel [32, 33].

Ignition delay

The time lag from the start to the end of combustion is periodically defined by Ignition delay. This usually occurs with definite intervals from phase changing that involve different crank angle rotations [34]. Figure 6 depicts the crank angle variations subjected to other blends. D90DR05B05 possesses the shortest ignition delay subjected to a crank angle starting position of 14 degrees to 19 degrees. This is because viscosity is lower than other blends. The main parameters that affect the ignition delay or ignition timing are equivalence ratio, air-fuel proportions, crank angle movements, and cylinder pressures [35, 36].

Emissions

Emissions of CO

The inadequate formation of carbon atoms with oxygen atoms results in emissions that are brown in appearance [37-39]. This causes lung failure. The protocol standards framed by the ASTM automotive fuel sector significantly lower the ppm emissions, resulting in lower suffocating problems [40]. The range designed for CO_2 emissions from the internal combustion engine is 0.2 to 0.5%, and If it exceeds 0.5%, it results in eye disorder[41-43]. Figure 7 shows the formations of CO at the different temperatures subjected to the piston from TDC to BDC. The most miniature CO formations are seen for the blend DR 100 attained at 0.10%. Still, for the diesel, it is seen by 0.14%; it is also seen that the highest emissions of 0.16% are attained for the blend D80DR08B12 because the higher content of butanol causes it to oxidize the blend quickly to accelerate the blend. It causes higher emissions compared to diesel [44-47]. The rapid decrease of 34.5% for the blend DR 100 than diesel

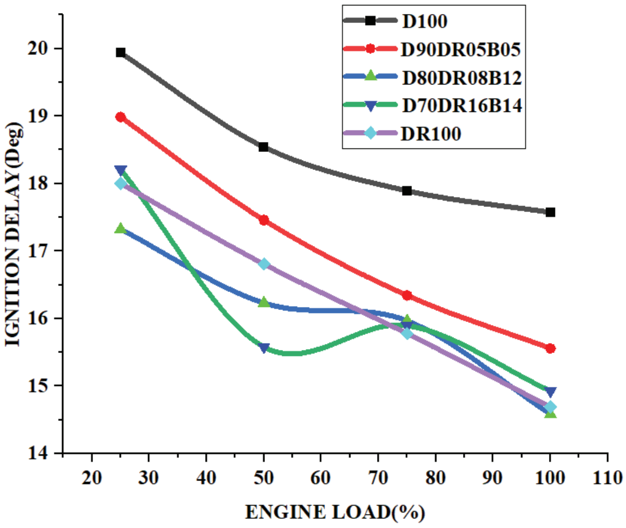

Figure 6. Ignition delay.

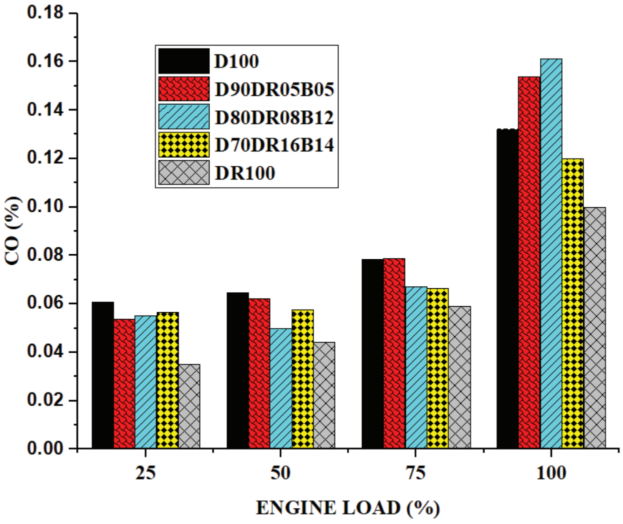

Figure 7. CO emissions.

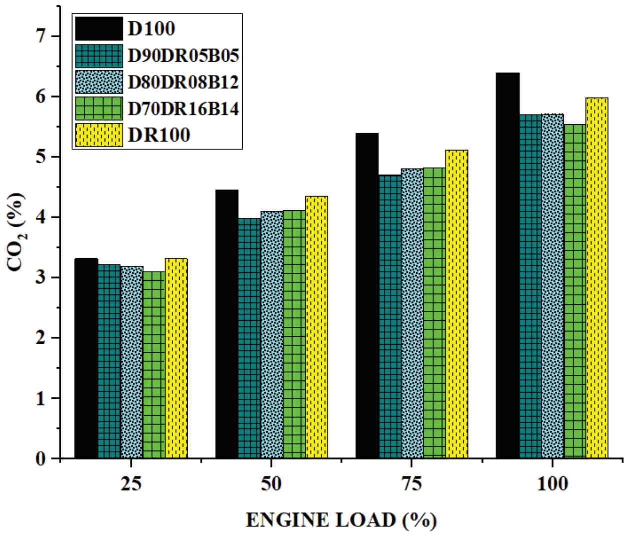

Figure 8. CO_2 emissions.

because of better viscosity offered for the blend DR 100 than diesel causes most minor CO emissions.

Emissions of CO_2

The excess formations of Oxygen molecules with the insufficient complement of carbon atoms concerned to different chemical reactions during the combustion phase results in carbon dioxide emissions. These emissions are very harmful to the Environment and affect lung cancer and suffocate problems[48-51]. The figure demonstrates the formation of carbon dioxide emissions at varying loads; it can identify or understand that at peak loads, the CO_2 emissions are much less for the blend D70DR16B14 because of the presence of butanol content limited to the 14% results in oxidized fuel, stabilize the fuel, evaporate the fuel tends to emit the fewer emissions ranged from 5% [52, 53]. But for diesel, with the same peak loads, the emissions are attained at 7%, the gradual decrease of 14.5% is decreased for the blend D70DR16B14 than diesel because of better combustion properties achieved by the butanol at elevated temperatures. One more reason for the lowest emissions formed for the D70DR16B14 blend is the lower cetane number, and the slightest difference in densities results in quicker evaporation of carbon molecules with oxygen molecules, resulting in fewer emissions [54-59].

Emissions of HC

Hydrocarbon emissions are continuous emissions of minute dispersed molecules formed due to incomplete combustion [60]. These emissions are hazardous to people who inhale above 50 ppm, which will cause stomach and eye disorders [61]. The incomplete formations of hydrogen molecules with carbon particles at the temperature range of 400°C result in hydrocarbon emissions [62, 63]. Figure 9 depicts the formation of emissions by hydrogen variations. Figure 9 shows that HC emissions are much less for the blend DR 100, followed by 30 ppm. Still, the diesel fuel in the HC formations is pretty high, 45 ppm, which DR 100 is less than 42.5% less than diesel; this is because of quicker the ignition delay occurred for the blend DR 100 because of the presence of carbon molecules with adequate oxygen causes significantly less emissions for the blend DR 100 than diesel and other blends [64].

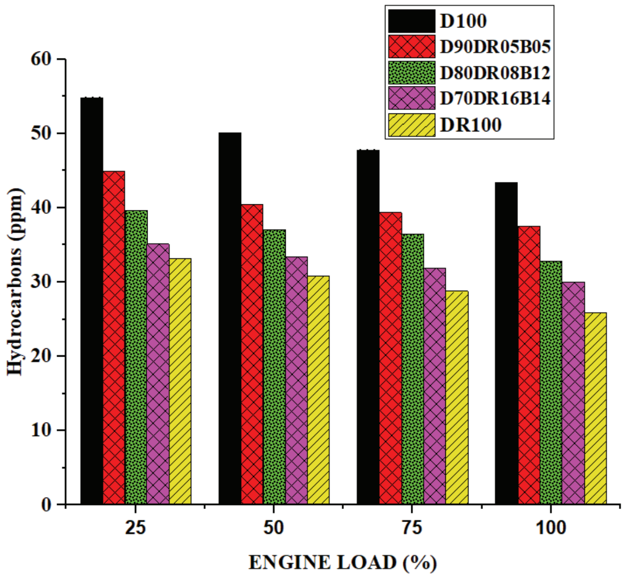

Figure 9. Hydrocarbon emissions.

Emissions of NO_x

The rate of emissions released due to the insufficient or inadequate supply of oxygen during elevated temperatures owing to inappropriate combustions is termed Nitrogen emissions [65]. These emissions are created or occur at the deep end of the tailpipe and disturb people in terms of heavy health problems, such as inhaling and severe eye

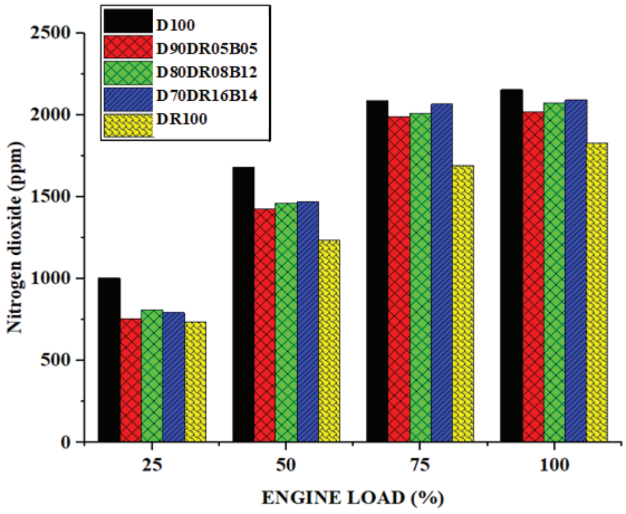

Figure 10. NO_X emissions.

defective problems [66, 67]. Figure 10 depicts the occurrence of Nitrogen emissions raised from low to high loads; From Figure 10, increasing the loads tends to form NO_X heavily [68, 69]. The blend DR100 emits less NO_X emissions than diesel and other blends because of an adequate supply of oxygen for pure Delox; Regina oil tends to oxidize, evaporate, and easily catch fire, achieving fewer emissions. The obtained NOx for the DR100 is 1700 ppm, but it is 2100 ppm for diesel. The decrease in ppm of NOx for the DR100 blend is 23.53% more than diesel.

CONCLUSION

The analysis of Delonix regina blends with the help of butanol, followed by different proportions, is examined thoroughly in the single-cylinder diesel engine. This investigation of the engine's performance, combustion, and emission characteristics was conducted, and the results obtained from the Delonix regina proportions with butanol were examined thoroughly with the help of diesel. This study shows that the combustions and emissions study is better for the Delonix Regina blends than diesel. Adding butanol to the Delonix Regina blends has more extreme ignition characteristics than diesel. The following results were achieved with the help of this analysis.

1 However, brake thermal efficiency is best for blending D90DR05B05, followed by 31%, because the D90DR05B05 blends have higher brake thermal efficiency and attain the very best calorific values with reduced viscosity.

2 The D90R05B05 blend is best, among other things, because it offers less viscosity and good heating values, Accelerating the blend at various ratios to attain optimal consumption is another reason for attaining the lowest BSFC for the blend D90R05B05. Adding the butanol content in limited proportions causes the cylinder pressures to be very high to achieve the optimal consumption of the blends.

3 The pressure rise is found for the blend D90DR05B05 at the rate of 68 bar. The result of butanal as the igniting alcohol with definite proportions leads to the combustion of the ignition properly compared to diesel.

4 It is understood that the blends D80DR08B12 and D90DR05B05 achieve the maximum heat release rate, followed by 85 kJ/CA degree and 83 Kj/ CA degree. The finite difference in HRR obtained for the D80DR08B12 blends is inferior to that of D90DR05B05 in terms of a 14.92% superior blend.

5 D90DR05B05 has the shortest ignition delay when subjected to a crank angle starting position of 14 degrees to 19 degrees. The higher the viscosity, the lower the ignition timing than other blends.

6 The blend DR 100 attained the most miniature CO formations at 0.10%, but diesel emissions were 0.14%. The highest emissions of 0.16% were attained for the blend D80DR08B12. The higher butanol content caused the blend to oxidize quickly, accelerating the blend and causing higher emissions than diesel.

7 CO_2 emissions are significantly lower for the blend D70DR16B14 because the presence of butanol content limited to 14% results in oxidizing the fuel, stabilizing the fuel, and evaporating the fuel tends to emit fewer emissions ranging from 5%. However, for diesel, with the same peak loads, the emissions are attained at 7%; the gradual decrease of 14.5% is decreased for the blend D70DR16B14 than diesel because of better combustion properties achieved by the butanol at elevated temperatures.

8 The HC emissions are very low for the blend DR 100, followed by 30 ppm, but the HC formations in diesel fuel are quite high, 45 ppm, less than 42.5% less than diesel.

9 The obtained NOx for the DR100 is 1700 ppm, but it is 2100 ppm for diesel. The decrease in NOx for the DR100 blend is 23.53% compared to diesel

NOMENCLATURE

Al_2O_3	Aluminium Oxide
BTE	Brake Thermal Efficiency
BDC	Bottom dead center
BSFC	Brake-specific fuel consumption
CO	Carbon Monoxide
CA	Crank Angle
CO_2	Carbon dioxide
CeO_2	Cerium oxide
D100	Pure diesel
D90DR05B05	90% Diesel 5% Delox Regina biodiesel and 5% butanol
D80DR08B12	80% Diesel 8% Delox Regina biodiesel and 12% butanol
D70DR16B14	70% diesel 16% Delox Regina biodiesel and 14% butanol
HC	Hydro Carbons
H_2	Hydrogen dioxide
HRR	Heat Release Rate
MFB	Mass Fraction Burnt
TDC	Top dead center
TiO_2	Titanium Oxide
PPM	parts per minute
NOx	Nitrogen oxide
DR100	Delox Regina biodiesel
EGT	Exhaust gas temperatures in °C
N	Revolutions per minute.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Algharib AM, Abd El Hakim AF, El-Khamissi HA, El-Hamamsy SM. Possibility of using Golden Shower (Cassia fistula) and Poinciana (Delonix regia) seeds oil as non-conventional feedstocks for the production of biodiesel in Egypt. J Ecological Engineer 2021;22:19–27. [CrossRef]

[2] Ardebili SMS, Solmaz H, İpci D, Calam A, Mostafaei M. A review on higher alcohol of fusel oil as a renewable fuel for internal combustion engines: Applications, challenges, and global potential. Fuel 2020;279:118516. [CrossRef]

[3] Barewar SD, Chougule SS. Thermal performance of double-pipe concentric heat exchanger with synthesized zinc oxide nanofluid. In: Singh S, Ramadesigan V, eds. Advances in Energy Research, Vol. 1. Springer Proceedings in Energy. Singapore: Springer; 2020. [CrossRef]

[4] Calam A, Aydoğan B, Halis S. The comparison of combustion, engine performance and emission characteristics of ethanol, methanol, fusel oil, butanol, isopropanol and naphtha with n-heptane blends on HCCI engine. Fuel 2020;266:117071. [CrossRef]

[5] Čedík J, Pexa M, Holúbek M, Aleš Z, Pražan R, Kuchar P. Effect of diesel fuel-coconut oil-butanol blends on operational parameters of diesel engine. Energies 2020;13:3796. [CrossRef]

[6] Chaichan MT. Combustion and emission characteristics of E85 and diesel blend in conventional diesel engine operating in PPCI mode. Thermal Sci Engineering Prog 2018;7:45–53. [CrossRef]

[7] Chaichan MT, Ekab NS, Fayad MA, Dhahad HA. PM and NOX emissions amelioration from the combustion of diesel/ethanol-methanol blends applying exhaust gas recirculation (EGR). IOP Conf Ser Earth Environ Sci 2022;961:012044. [CrossRef]

[8] Chaichan MT, Fayad MA, Al Ezzi A, Dhahad HA, Megaritis T, Yusaf T, et al. Ultralow sulfur diesel and rapeseed methyl ester fuel impact on performance, emitted regulated, unregulated, and nanoparticle pollutants. ACS Omega 2022;7:26056–26075. [CrossRef]

[9] Devarajan Y, Beemkumar N, Ganesan S, Arunkumar T. An experimental study on the influence of an oxygenated additive in diesel engine fuelled with neat papaya seed biodiesel/diesel blends. Fuel 2020;268:117254. [CrossRef]

[10] Dhahad HA, Fayad MA, Chaichan MT, Jaber AA, Megaritis T. Influence of fuel injection timing strategies on performance, combustion, emissions and particulate matter characteristics fueled with rapeseed methyl ester in modern diesel engine. Fuel 2021;306:121589. [CrossRef]

[11] Dhar A, Kevin R, Agarwal AK. Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a single cylinder DICI engine. Fuel Process Technol 2012;97:118–129. [CrossRef]

[12] Dwivedi G. Performance evaluation of diesel engine using biodiesel from Pongamia oil. Int J Renew Energy Res 2013;3:325–330.

[13] Efe Ş, Ceviz MA, Temur H. Comparative engine characteristics of biodiesels from hazelnut, corn, soybean, canola and sunflower oils on DI diesel engine. Renew Energy 2018;119:142–151. [CrossRef]

[14] Ekaab NS, Hamza NH, Chaichan MT. Performance and emitted pollutants assessment of diesel engine fuelled with biokerosene. Case Stud Therm Engineer 2019;13:100381. [CrossRef]

[15] Elishav O, Mosevitzky Lis B, Miller EM, Arent DJ, Valera-Medina A, Grinberg Dana A, et al. Progress and prospective of nitrogen-based alternative fuels. Chem Rev 2020;120:5352–5436. [CrossRef]

[16] Elkelawy M, Bastawissi HAE, Esmaeil KK, Radwan AM, Panchal H, Sadasivuni KK, et al. Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends. Fuel 2019;255:115791. [CrossRef]

[17] Eriksson L, Andersson I. An analytic model for cylinder pressure in a four-stroke SI engine. SAE Trans 2002:726–733. [CrossRef]

[18] Fayad MA, Abd AO, Chaichan MT, Dhahad HA, Al Ezzi A. Investigation the combined effects of exhaust gas recirculation (EGR) and alcohol-diesel blends in improvement of NOX-PM trade-off in compression ignition (CI) diesel engine. IOP Conf Ser Earth Environ Sci 2022;961:012048. [CrossRef]

[19] Fayad MA, Chaichan MT, Dhahad HA. The effect of first generation biofuel on emission characteristics under variable conditions of engine speeds and loads in diesel engine. J Physics Conf Ser 2021;1973:012041. [CrossRef]

[20] Fayad MA, Ibrahim SI, Omran SH, Martos FJ, Badawy T, Al Jubori AM, et al. Experimental effect of CuO2 nanoparticles into the RME and EGR rates on NOX and morphological characteristics of soot nanoparticles. Fuel 2023;331:125549. [CrossRef]

[21] Fayad MA, Sobhi M, Chaichan MT, Badawy T, Abdul-Lateef WE, Dhahad HA, et al. Reducing soot nanoparticles and NOX emissions in CRDI diesel engine by incorporating TiO2 nano-additives into biodiesel blends and using high rate of EGR. Energies 2023;16:3921. [CrossRef]

[22] Gawale GR, Srinivasulu GN. Experimental investigation of propanol dual fuel HCCI engine performance: Optimization of propanol mass flow rate, impact of butanol blends (B10/B20/B30) as fuel substitute for diesel. Fuel 2020;279:118535. [CrossRef]

[23] Golshany HS. Extraction and evaluation of carotenoids from Delonix regina (Delonix regia) flowers [Master's thesis]. Cairo University; 2019.

[24] Han J, Wang S, Vittori RM, Somers LMT. Experimental study of the combustion and emission characteristics of oxygenated fuels on a heavy-duty diesel engine. Fuel 2020;268:117219. [CrossRef]

[25] Heo I, You YW, Lee JH, Schmieg SJ, Yoon DY, Kim CH. Urealess NOX reduction by carbon monoxide in simulated lean-burn exhausts. Environ Sci Technol 2020;54:8344–8351. [CrossRef]

[26] Huang Y, Li Y, Luo K, Wang J. Biodiesel/butanol blends as a pure biofuel excluding fossil fuels: Effects on diesel engine combustion, performance, and emission characteristics. Proc Inst Mech Eng Part D J Automob Eng 2020;234:2988–3000. [CrossRef]

[27] Jena SP, Acharya SK. Investigation on influence of thermal barrier coating on diesel engine performance and emissions in dual-fuel mode using upgraded biogas. Sustain Environ Res 2019;29:1–10. [CrossRef]

[28] Karagöz M. Investigation of performance and emission characteristics of a CI engine fuelled with diesel-waste tire oil-butanol blends. Fuel 2020;282:118872. [CrossRef]

[29] Karmakar B, Ghosh B, Samanta S, Halder G. Sulfonated catalytic esterification of Madhuca indica oil using waste Delonix regia: L16 Taguchi optimization and kinetics. Sustain Energy Technol Assess 2020;37:100568. [CrossRef]

[30] Kawale HD, Kishore N. Comparative study on pyrolysis of Delonix regia, pinewood sawdust and their co-feed for plausible bio-fuels production. Energy 2020;203:117921. [CrossRef]

[31] Khan H, Soudagar MEM, Kumar RH, Safaei MR, Farooq M, Khidmatgar A, et al. Effect of nano-graphene oxide and n-butanol fuel additives blended with diesel—Nigella sativa biodiesel fuel emulsion on diesel engine characteristics. Symmetry 2020;12:961. [CrossRef]

[32] Kinoshita H, Türkan H, Vucinic S, Naqvi S, Bedair R, Rezaee R, et al. Carbon monoxide poisoning. Toxicol Rep 2020;7:169-173. [CrossRef]

[33] Kumar AN, Kishore PS, Raju KB, Ashok B, Vignesh R, Jeevanantham AK, et al. Decanol proportional effect prediction model as additive in palm biodiesel using ANN and RSM technique for diesel engine. Energy 2020;213:119072. [CrossRef]

[34] Kumar KS, Muniamuthu S. Design and fabrication of nickel-chromium reinforced 2-stage energy efficient pyrolysis reactor for waste plastics applications. Int J Ambient Energy 2024;45:2288148. [CrossRef]

[35] Kumar V, Singh AP, Agarwal AK. Gaseous emissions (regulated and unregulated) and particulate characteristics of a medium-duty CRDI transportation diesel engine fueled with diesel-alcohol blends. Fuel 2020;278:118269. [CrossRef]

[36] Kumar VD, Mrityunjayaswamy KM, Chinnapandian M, Hemadri VB. Experimental determination on the performance and emission characteristics of Delonix regia oil methyl ester and its blends on single-cylinder diesel engine. Mater Today Proc 2021;45:8120–8124. [CrossRef]

[37] Li Y, Lou B, Abubakar S, Wu G. Skeletal mechanism for i-propanol-n-butanol-ethanol (IBE) and n-butanol combustion in diesel engine. Fuel 2021;302:121136. [CrossRef]

[38] Likhanov VA, Lopatin OP. Investigation of the ignition delay period in the diesel combustion chamber when working on an alcohol-fuel emulsion. IOP Conf Ser Mater Sci Engineer 2020;862:062027. [CrossRef]

[39] Likhanov VA, Lopatin OP. Investigation of the speed regime of tractor diesel engine running on natural gas with recirculation. IOP Conf Ser Mater Sci Engineer 2018;457:012011. [CrossRef]

[40] Lin CY, Lin HA. Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. Fuel 2006;85:298–305. [CrossRef]

[41] Mahapatra S, Kumar D, Singh B, Sachan PK. Biofuels and their sources of production: A review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus. Energy Nexus 2021;4:100036. [CrossRef]

[42] Mahla SK, Ardebili SMS, Sharma H, Dhir A, Goga G, Solmaz H. Determination and utilization of optimal diesel/n-butanol/biogas derivation for small utility dual fuel diesel engine. Fuel 2021;289:119913. [CrossRef]

[43] Mehregan M, Moghiman M. Effects of nano-additives on pollutants emission and engine performance in a urea-SCR equipped diesel engine fueled with blended-biodiesel. Fuel 2018;222:402–406. [CrossRef]

[44] Mendiara T, García-Labiano F, Abad A, Gayán P, de Diego LF, Izquierdo MT, Adánez J. Negative CO2 emissions through the use of biofuels in chemical looping technology: A review. Appl Energy 2018;232:657-684. [CrossRef]

[45] Mickevicius T, Slavinskas S, Labeckas G. Performance and emissions of diesel engine operating on biodiesel and butanol blends. Eng Rural Dev 2020;19:1381–1386. [CrossRef]

[46] Mujtaba MA, Kalam MA, Masjuki HH, Gul M, Soudagar MEM, Ong HC, et al. Comparative study of nanoparticles and alcoholic fuel additives-biodiesel-diesel blend for performance and emission improvements. Fuel 2020;279:118434. [CrossRef]

[47] Mukherjee M, Goswami G, Mondal PK, Das D. Biobutanol as a potential alternative to petroleum fuel: Sustainable bioprocess and cost analysis. Fuel 2020;278:118403. [CrossRef]

[48] Olagbende OH, Falowo OA, Latinwo LM, Betiku E. Esterification of Khaya senegalensis seed oil with a solid heterogeneous acid catalyst: Modeling, optimization, kinetic and thermodynamic studies. Cleaner Eng Technol 2021;4:100200. [CrossRef]

[49] Örs İ, Sarıkoç S, Atabani AE, Ünalan S. Experimental investigation of effects on performance, emissions and combustion parameters of biodiesel–diesel–butanol blends in a direct-injection CI engine. Biofuels 2020;11:121–134. [CrossRef]

[50] Patra SC, Vijay M, Panda AK. Production and characterisation of bio-oil from Gold Mohar (Delonix regia) seed through pyrolysis process. Int J Ambient Energy 2017;38:788–793. [CrossRef]

[51] Peirce DM, Alozie NSI, Hatherill DW, Ganippa LC. Premixed burn fraction: Its relation to the variation in NOx emissions between petro-and biodiesel. Energy Fuels 2013;27:3838–3852. [CrossRef]

[52] Praveena V, Martin MLJ. A review on various after-treatment techniques to reduce NOx emissions in a CI engine. J Energy Inst 2018;91:704–720. [CrossRef]

[53] Provataris SA, Savva NS, Chountalas TD, Hountalas DT. Prediction of NOx emissions for high-speed DI diesel engines using a semi-empirical, two-zone model. Energy Convers Manage 2017;153:659–670. [CrossRef]

[54] Raju VD, Venu H, Subramani L, Kishore PS, Prasanna PL, Kumar DV. An experimental assessment of prospective oxygenated additives on the diverse characteristics of diesel engine powered with waste tamarind biodiesel. Energy 2020;203:117821. [CrossRef]

[55] Ramalingam S, Subramanian S, Subramanian A. Utilization of pyrolytic oil and hydrogen enriched syngas from single feedstock (Delonix regia) through pyrolysis process and its influence on performance and emission characteristics in CI engine. Int J Hydrogen Energy. 2022;47:36749–36762. [CrossRef]

[56] Ravichandra Ganesh P, Hemachandra Reddy K, Babu JM, Sarath Chandra M. Experimental investigation of performance, emission and combustion characteristics of a DI-diesel engine fuelled with aqueous cerium oxide and aqueous aluminium oxide nanoparticle additives. In: Maurya A, Srivastava AK, Jha PK, Pandey SM, eds. Recent Trends in Mechanical Engineering. Singapore: Springer; 2021. pp. 85–96. [CrossRef]

[57] Sayin C, Balki MK. Effect of compression ratio on the emission, performance and combustion characteristics of a gasoline engine fueled with iso-butanol/gasoline blends. Energy 2015;82:550–555. [CrossRef]

[58] Sayin C, Canakci M. Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine. Energy Convers Manage 2009;50:203–213. [CrossRef]

[59] Sharma A, Pali HS, Kumar M, Singh NK, Rahim EA, Singh Y, Gupta NK. Effect of α-aluminium oxide nano additives with Sal biodiesel blend as a potential alternative fuel for existing DI diesel engine. Energy Environ 2022:0958305X221133257. [CrossRef]

[60] Sharma PO, Barewar SD, Unune DR, Chougule SS. A comparative assessment of Ag/ZnO hybrid nanofluid with ZnO nanofluid to augment the heat transfer rate during pool boiling. Proceedings of the 26th National and 4th International ISHMT-ASTFE Heat and Mass Transfer Conference; 2021 Dec 17–20; IIT Madras, Chennai-600036, Tamil Nadu, India.

[61] Sivalakshmi S, Balusamy T. Effect of biodiesel and its blends with diethyl ether on the combustion, performance and emissions from a diesel engine. Fuel 2013;106:106–110. [CrossRef]

[62] Venkatesan DK, Hemadri VB, Marimuthu C, Mrityunjayaswamy KM. Esterified papaya oil and flamboyant oil as a fuel on single-cylinder diesel engine. J Adv Res Fluid Mech Therm Sci 2022;99:90–103. [CrossRef]

[63] Venu H, Appavu P. Combustion and emission characteristics of tamarind seed biodiesel-diesel blends in a compression ignition engine. Int J Ambient Energy 2021;42:1441–1446. [CrossRef]

[64] Verma P, Dwivedi G, Behura AK, Patel DK, Verma TN, Pugazhendhi A. Experimental investigation of diesel engine fuelled with different alkyl esters of Karanja oil. Fuel 2020;275:117920. [CrossRef]

[65] Wu G, Wu D, Li Y, Meng L. Effect of acetone-n-butanol-ethanol (ABE) as an oxygenate on combustion, performance, and emission characteristics of a spark ignition engine. J Chem 2020;7468651. [CrossRef]

[66] Xiao H, Guo F, Wang R, Yang X, Li S, Ruan J. Combustion performance and emission characteristics of diesel engine fueled with iso-butanol/biodiesel blends. Fuel 2020;268:117387. [CrossRef]

[67] Yesilyurt MK. The effects of the fuel injection pressure on the performance and emission characteristics of a diesel engine fuelled with waste cooking oil biodiesel-diesel blends. Renew Energy 2019;132:649–666. [CrossRef]

[68] Zhang Z, Tian J, Xie G, Li J, Xu W, Jiang F, Huang Y, Tan D. Investigation on the combustion and emission characteristics of diesel engine fueled with diesel/methanol/n-butanol blends. Fuel 2022;314:123088. [CrossRef]

[69] Zöldy M. Fuel properties of butanol-hydrogenated vegetable oil blends as a diesel extender option for internal combustion engines. Period Polytech Chem Eng 2020;64:205-212. [CrossRef]