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Evaluating the Influence of Cetane Improver Additives on the Outcomes of a Diesel Engine Characteristics Fueled with Peppermint Oil Diesel Blend

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Abstract: This paper aims to evaluate the impact of cetane improvers on the combustion, performance and emission characteristics of a compression ignition engine fueled with a 20% peppermint bio-oil/diesel blend (P20). It is hypothesized that the low viscosity and boiling point of peppermint oil could improve the atomization characteristics of the fuel. However, the usage of peppermint oil is restricted due to its low cetane index. To improve this, Diethyl Ether (DEE) and Di- tertiary Butyl Peroxide (DTBP) are added to the P20 blend. The tests are performed in a single-cylinder naturally aspirated water-cooled diesel engine and results indicate that NOx emission for P20 + DEE and P20 + DTBP is decreased by 10.4% and 9.8%, respectively, when compared to P20 at full load condition. Among these two cetane improvers, DTBP is more effective in reducing the CO, HC and smoke emission and the performance of the engine was reported to be higher for P20 + DTBP blends.

Keywords: DEE; DTBP; peppermint; biofuel; combustion; emission

1. Introduction

Rapid industrialization and increased transportation had a significant impact on global warming and climate change. In countries like India, diesel engines are widely used for transportation and most industrial applications due to the higher efficiency and torque produced by diesel engines when compared with petrol engines [1]. These diesel engines also emit large amount of exhaust pollutants like carbon dioxide, hydrocarbon, nitrogen oxide, and soot particles. Among these pollutants, carbon dioxide emission plays a significant part in inducing global warming/climate change [2]. Life cycle emission of CO_2 is lower for eco-friendly biofuels, which can help to decelerate global warming [3]. Many researchers tried various biofuels, since the oil obtained from waste fatty acids, animal fat, vegetables and other biodegradable products have physical and chemical properties very similar to diesel fuel [4]. However, direct vegetable oil usage in diesel engines is not gaining importance due to its unfavourable properties such as high viscosity and low boiling point. Despite the use of viscosity-improvers having been advocated for [5], and hydro-treating gaining considerable attention [6], transesterification continues to be the main-frame process to reduce the high viscosity vegetable oil into low viscosity biodiesel [7]. This pertains to considerably lower infrastructural investments required to produce fatty acid methyl esters (FAME), yet tradeoffs with insufficient chemical properties to meet most automotive fuel quality standards as a stand-alone fuel. Due to these reasons, 7–20 percent of biodiesel blended with diesel is considered an acceptable solution, depending on the application [8].

Many researchers investigated alcohols such as methanol, ethanol [9,10] and higher alcohols such as isobutanol, n-butanol and pentanol as compression ignition (CI) engine fuels [11,12]. Among alcohol fuels, n-butanol has superior stability and vapour lock characteristics. Even though the alcohol fuels have lower cetane number and lower calorific value, it is highly admired for its lower boiling point and viscosity which aids to better atomization and fuel-air mixing [13]. Researchers also tried blending different types of fuels with diesel to form ternary blends to improve the fuel characteristics [14–17]. However, no significant improvement was noticed due to the blending of fuels with different physio-chemical properties. Similar to alcohols, essential oils which are well known for their lower viscosity such as pine oil, eucalyptus oil, lemongrass oil and lemon peel oil have also been tried as a potential biofuel in diesel engines [18–22]. Even though both alcohols and essential oils have a lower cetane number, they can be used in CI engine by altering their ignition properties. Fuels' cetane number can be increased by reducing the fuel aromatic content through hydro-treating or by adding cetane improvers. The cetane number further depends on the composition of the fuel and its molecular structure [23]. Cetane improver can be added with low cetane fuels to improve the ignition qualities and reduce NO_X emissions [24]. It will form free radicals by promoting the initiation reaction. Many cetane improvers like Di Ethyl Ether (DEE), Ethyl Hexyl Nitrate (EHN), Di Tertiary Butyl Peroxide (DTBP) are tried by many researchers for low cetane fuels in CI engine. Investigators Vallinayagam et al. examined the impact of cetane improvers: Iso Amyl Nitrate (IAN) and DTBP on 50% pine oil and 50% diesel blends in a diesel engine. They reported that NO_X emission is decreased for DTBP blends by 6.4% more than IAN blends and also that performance was improved for DTBP blends [25]. Researchers Abhishek Paul et al. reported the effect of 5% and 10% DEE on Ethanol diesel blends in a diesel engine. NO_X and particulate matter emission were reduced for the DEE-Ethanol blend. Particularly, a 25.95% reduction in NO_X emission for 10% DEE blends was achieved [26]. Zhang et al. observed that the soot emission decreased by 80% for EHN addition into Dimethyl furan diesel blends and maximum pressure increases with an increase in the proportion of EHN. It was concluded that NO_X emission increases slightly but THC emissions were drastically reduced [27]. Thiyagarajan Subramanian et al. (2018) examined the effects of Diglyme as a cetane enhancer in camphor oil diesel blends. They reported the improvement of ignition characteristics with the addition of 10% Diglyme. It was concluded that the cold starting problem and higher NO_X emission were overcome by adding Diglyme to Camphor oil without affecting the performance [28]. Purushothaman et al. examined the addition of DEE to orange oil blends on evaluating emission. They reported that DEE is a potential additive for NO_X emission reduction but it also influences the increase in the HC emission [29].

The possibility of running diesel engines with lower cetane fuels has encouraged us to investigate the use of peppermint oil in a CI engine through the performance, emission and combustion characters of the engine. The tests were conducted for different load values at a constant speed of 1500 rpm. From our previous study with peppermint oil in a CI engine, 20% peppermint oil mixture is taken as the optimum blend at higher load condition [30]. The P20 blend affects the fuel ignition and increases the NO_X emission due to a lower cetane value of the peppermint oil. The use of 20% peppermint oil blended with two different ignition improvers, namely, DEE and DTBP, is considered in this study to reduce the emissions.

2. Materials and Methods

2.1. Test Fuels

Peppermint oil is an essential-oil based, low cetane fuel obtained from the peppermint leaves using the steam distillation process. The significant components of peppermint oil being eucalyptol, menthone, and menthyl acetate. The cetane improvers DEE and DTBP were procured from the sigma Aldrich. Additionally, diesel fuel and peppermint oil were purchased from the local suppliers. Five percent DEE is mixed with twenty percent peppermint oil denoted as P20 + DEE and 2% of DTBP was added with P20 denoted as P20 + DTBP, respectively. Blends are mixed using an ultrasonic agitator to create thorough mixing. The properties of test fuels, additives and the blends prepared are listed in Table 1.

Table 1. Properties of test fuels, blends and additives.

Properties	Diesel	Peppermint Oil	P20	DEE	DTBP	P20 + DEE	P20 + DTBP	Measurement Standards
Density (g/m^3)	0.83	0.89	0.843	0.713	0.79	0.836	0.84	ASTM D1298
Calorific Value (MJ/kg)	42.5	32	40.4	33.9	-	40.38	40.32	ASTM D240
Kinematic Viscosity (cSt)	2.9	3.3	2.99	1.089	0.9	2.9	2.92	ASTM D445
Flash Point (°C)	54	82	62	−45	6	57	60	ASTM D92
Cetane Index	52	18	45	>125	-	59	53	ASTM D976
Boiling point (°C)	180–340	140–230	-	35	109	-	-	ASTM D1160
Sulphur content (ppm)	50	0	-	-	-	-	-	ASTM D7039

2.2. Experimental Setup and Test Measurements

A water-cooled single-cylinder diesel engine coupled with an eddy current dynamometer was used in this study. The schematic of the experimental setup is depicted in Figure 1. The engine compression ratio is set at the standard value of 17.5:1, with the necessary swirl motion created using a hemispherical combustion chamber. The specifications of the test engine are mentioned in Table 2. An inductive pickup sensor was used to sense the engine speed and indicated the speed through a digital rpm indicator.

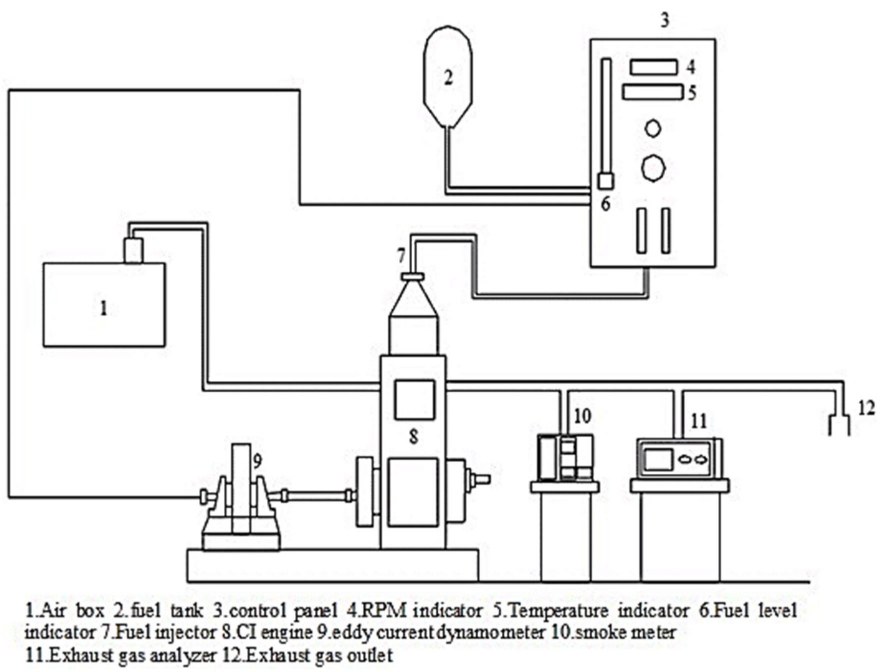


Figure 1. Schematic diagram of the experimental setup.

Table 2. Specification of the test engine setup.

Details	Specification
Type	Water-cooled, 4 stroke, compression ignition, direct injection
Make and Model	Kirloskar TV1 model
Rated power & speed	5.2 kW & 1500 rpm
Number of cylinder	Single cylinder
Compression ratio	17.5:1
Bore & stroke	87.5 mm & 110 mm
Method of loading	Eddy current dynamometer
Type of injection	Mechanical pump-nozzle injection
Injection timing	23° before TDC
Injection pressure	220 bar
Combustion chamber	Hemispherical open type
No of Injector nozzle hole	3
Nozzle hole diameter	0.3 mm

The 10 cc fuel consumed by the engine was calculated on a volumetric basis using a stopwatch and a two-way cock burette is used to calculate the flow rate of the fuel. The in-cylinder pressure was measured using a pressure transducer fitted on the cylinder head and the crank angle was recorded using an encoder fixed at the end of the crankshaft. The crank angle and pressure values are observed in the personal computer with the help of the data acquisition system which is used to process the signals from different sensors. At each crank angle, pressure data were recorded for 100 consecutive cycles and averaged. By using Engine soft software, HRR was computed from the measured cylinder pressure data. Emissions such as HC, CO and NOx are measured using AVL Di gas analyzer and smoke is measured using AVL 437C Smoke meter.

In the beginning, the engine was operated to run for 15 min in no-load condition to attain the steady-state operating condition. Additionally, after the change of each of each fuel blend, the engine was operated for 10 min in 50% load condition. The fuel mixtures filled in separate cans are introduced into the engine through a by-pass tube present in the top of the fuel level indicator unit. Engine speed is maintained at 1500 rpm during the experiments. Readings are taken for different load values from 0% load condition to 100% load condition in 25% increments. Exhaust gas emissions such as HC, CO, and NOx are measured using AVL digas analyser using a small probe at the tail pipe exhaust section of the engine. The analyser works under the nondispersive infrared (NDIR) principle to quantify these emissions. Smoke emission is measured using AVL smoke meter which uses opacimeter principle which is connected through a separate probe. HC and NOx emissions are measured in parts per million (ppm), whereas, CO and Smoke are measured in % vol. basis. Tests are repeated thrice to get higher reliability and the averaged values are used to determine the characteristics. Uncertainty indicates deviation in measured value based on errors. The uncertainties and accuracy of measuring instruments used in this experiment are listed in Table 3. The total uncertainties that prevailed in this experiment were calculated using the equation as stated in [31] and it was found to be 2.7%.

Table 3. List of instruments used along with their percentage uncertainty values.

Measured Parameter	Instrument Used	Uncertainty	Measurement Technique
Load	Strain gauge, Sensotronics Sanmar	±0.2	Load cell
Speed	Kubler, Germany	±0.2	Inductive pickup principle
Fuel flow measurement	Differential pressure transmitter	±1	Volumetric measurement
CO	AVL Di gas Analyser	±0.2	NDIR technique
HC	AVL Di gas Analyser	±0.1	NDIR technique
NOx	AVL Di gas Analyser	±0.2	NDIR technique
Smoke	AVL Smoke meter	±1	Opacimeter
Pressure Pick up	PCB, piezotronics	±0.1	Magnetic pickup principle
Crank angle encoder	Kubler, Germany	±0.2	Magnetic pickup principle

3. Results and Discussion

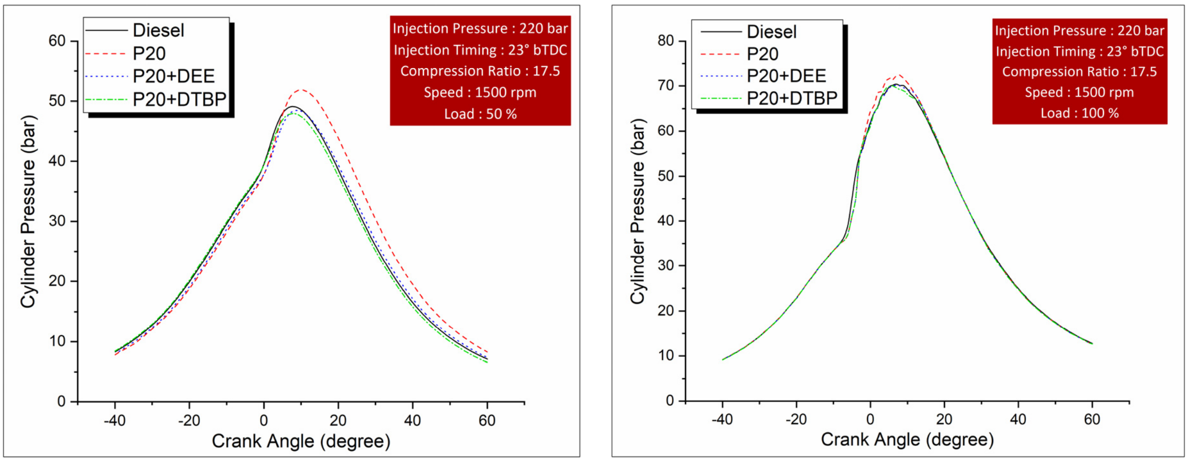
The combustion, performance and emission outcomes of the single-cylinder constant speed engine when operated with blends of peppermint oil are given in this section.

3.1. Combustion Analysis

This section presents the combustion results such as cylinder pressure, heat release rate, ignition delay and combustion duration obtained for different peppermint oil blends.

3.1.1. Cylinder Pressure

Figure 2 indicates the in-cylinder pressure variation for P20, P20 + DEE, P20 + DTBP for 50% load value (Figure 2a) and 100% load value (Figure 2b) with respect to crank angle. In-cylinder pressure indicates the behavior of the engine operation. In CI Engine, the peak pressure of the cylinder relies on the amount of fuel burned in the premixed phase of combustion [32]. Among the various fuel blends, P20 experiences higher cylinder pressure during both the load conditions. The increase in peak cylinder pressure is due to a prolonged premixed combustion phase caused by higher ignition delay due to the lower cetane value of the biofuel, which facilitates more fuel to be accumulated and better fuel-air mixing process. Thus, more fuel is combusted in a shorter period leading to the increase in cylinder pressure. At 100% load, for P20 + DEE blend the peak in-cylinder pressure is 3.2% lesser than P20 but it is still higher than diesel. Similarly, at 50% load condition the difference between the two blends is 5.8%. Researchers reported that ignition delay was increased when DEE was added with diesel [12]. Contrary to this observation, ignition delay was slightly reduced while adding DEE with P20 blends in both the cases. This may be due to the reactions with diesel aromatics being suppressed by the chemical composition of peppermint oil and thus contributes to the drop in peak in-cylinder pressure. P20 + DTBP on the other hand exhibits a reduced cylinder pressure due to the reduction in ignition delay period due to its self-accelerated thermal decomposition nature [33].



(**a**) (**b**)

Figure 2. Cylinder pressure variation for test fuel blends, (**a**) at 50% load; (**b**) at 100% load.

3.1.2. Heat Release Rate

The rate of heat release for peppermint oil blends is shown in Figure 3 for 50% load value (Figure 3a) and 100% load value (Figure 3b). At both the load conditions, the peak HRR value for P20 blend is higher than diesel. This is due to the increase in ignition delay period associated with the usage of peppermint oil due to its lower cetane value. Extended ignition delay period accumulates more fuel, thus releases more heat energy during the combustion [34]. When DTBP is added with peppermint oil diesel blends, the peroxide group generates free alkaline-oxy radicals during the evaporation process, which leads to better ignition attributes of the fuel blends. Accordingly, early SOC occurs for P20 + DTBP blend and the HRR curve swings away from TDC, thereby tumbling the level of Peak HRR. Thus, the DTBP blend shows the least Ignition delay period and also has the lowest Peak HRR value of 71.2 kJ/m^3. A similar response is seen for DTBP even at 50% load value, showing a reduction of 7.9% compared with P20 blend. Addition of DEE improves the overall cetane value of the blend and reduces the ignition delay period but the cooling nature of DEE due to its higher latent heat property, slightly delays the start of combustion. P20 + DEE blend has a peak HRR value of 73.24 kJ/m^3 at 100 % load value and 50.84 kJ/m^3 at 50% load value.

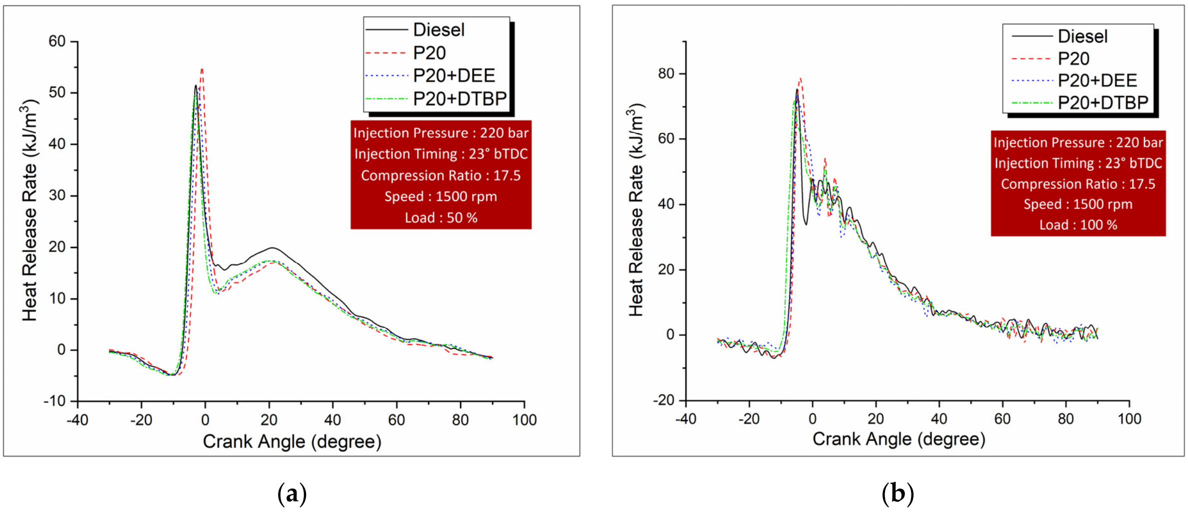


Figure 3. HRR variation for test fuel blends, (**a**) at 50% load; (**b**) at 100% load.

3.1.3. Ignition Delay and Combustion Duration

The combustion duration and ignition delay period at 50% load and 100% load values are shown in Figure 4a,b, respectively. The values were calculated from the rate of heat release (ROHR) for all the four blends (diesel, P20, P20 + DEE, P20 + DTBP) obtained at both the load conditions. Ignition delay is measured from the difference between the crank angle at the start of injection (SOI) and the start of combustion (SOC).

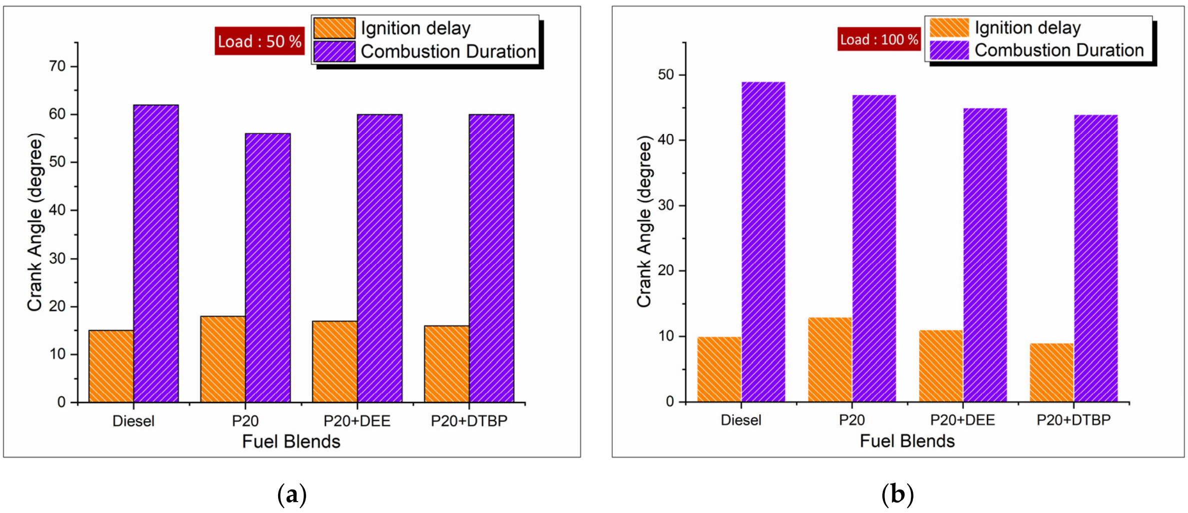


Figure 4. Ignition delay and combustion duration variation for test fuel blends, (**a**) at 50% load; (**b**) at 100% load.

The ignition delay was higher in both the load conditions for P20 blends due to their reduced cetane value. With the addition of cetane improvers, ignition delay was significantly reduced. However, the ignition delay of P20 with DEE's addition was not considerably reduced due to the retardation of dynamic injection timing due to its high latent heat and lower viscosity. Combustion duration was computed based on the crank angle difference between 90% cumulative HRR and SOC. The duration of combustion for diesel and P20 at full load condition are 49 and 46 crank angle degree (CAD), respectively. This combustion duration reduction for P20 blends compared with diesel is due to the rapid burning rate of P20 blends as more fuel being burnt due to the higher ignition delay period. Moreover, the blends with peppermint oil enhance the combustion due to the excess oxygen content, and thus a relatively lower combustion duration period than diesel fuel is noticed in both the load conditions. The combustion duration of P20 + DTBP blend is 44 CAD at full load condition and 60 CAD at 50% load condition. This is comparatively lesser than both P20 and diesel. This reduction indicates that a quicker combustion process happens while mixing DTBP with peppermint oil blend.

3.2. Performance Analysis

This section presents the results that determine the engine's performance, such as brake-specific fuel consumption and brake thermal efficiency.

3.2.1. Brake Specific Fuel Consumption

BSFC implies the amount of fuel consumed by the engine for producing unit brake power. The BSFC variation for various test fuel blends is indicated in Figure 5. BSFC for the P20 blend is less than diesel at full load condition. This may be ascribed to better fuel properties of peppermint oil, leading to an improved combustion process. Adding 5% DEE to peppermint oil blend decreased the BSFC further at all loads. Even though DEE's calorific value is lower compared to diesel, its higher oxygen content of around 21.6% helps to improve the combustion efficiency, leading to lesser energy requirement. The results obtained match with the previous research work done by Amr Ibrahim et al. [35] for biodiesel DEE blend. BSFC of P20 + DTBP blend is less than P20 due to better burning, which is influenced by an increase in the blends' cetane number. As DTBP undergoes homolysis and efficiently induces the combustion process, more fuel molecules were involved in the combustion, thereby reducing the overall BSFC value. Compared with diesel at full load, 7.47% and 11.37% reduction is noticed for P20 + DEE and P20 + DTBP, respectively.

3.2.2. Brake Thermal Efficiency

BTE indicates the work output to the energy supplied in an engine. Enhanced ignition and combustion process obtained by increasing the Peppermint oil's cetane value using Diethyl ether and di tert butyl peroxide leads to the improvement in BTE. From Figure 6, it can be seen that BTE for P20 + DTBP is superior to P20 + DEE and P20 blends at all load values. The improvement in BTE with the usage of 20% peppermint oil can be attributed to the properties of the oil itself. The higher oxygen concentration with lower viscosity and boiling point helped to improve the atomization of the fuel molecules which leads to better evaporation. This improves the combustion process leading to the increase in BTE of the P20 blends. Though there was an improvement of about 4.31% compared to diesel at full load condition, further improvement might be possible considering the bio oil's lower cetane value. Hence, DTBP and DEE are added to this P20 blend. With the addition of DEE and DTBP, the improvement achieved is shown in the graph. DEE increases the fuel's cetane value, whereas DTBP improves the ignition quality by self-accelerated decomposition and reduces the ignition delay period [36]. Higher brake thermal efficiency for P20 + DTBP may be attributed to higher in-cylinder pressure induced by the blends' enhanced fuel properties. It is also reflected in reduced combustion duration for these fuel blends. Enhancements in the engine's performance as determined with the present study concurs well with the reports of Vedharaj et al., that pine oil diesel blends with DTBP as an ignition enhancer [25].

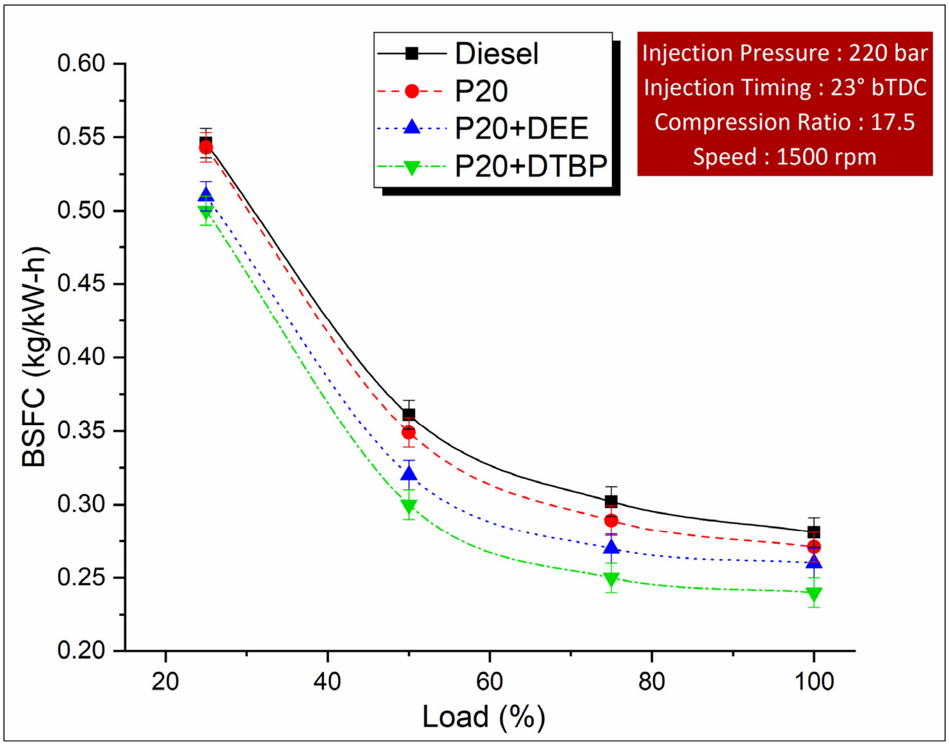


Figure 5. BSFC variation for test fuel blends at different load condition.

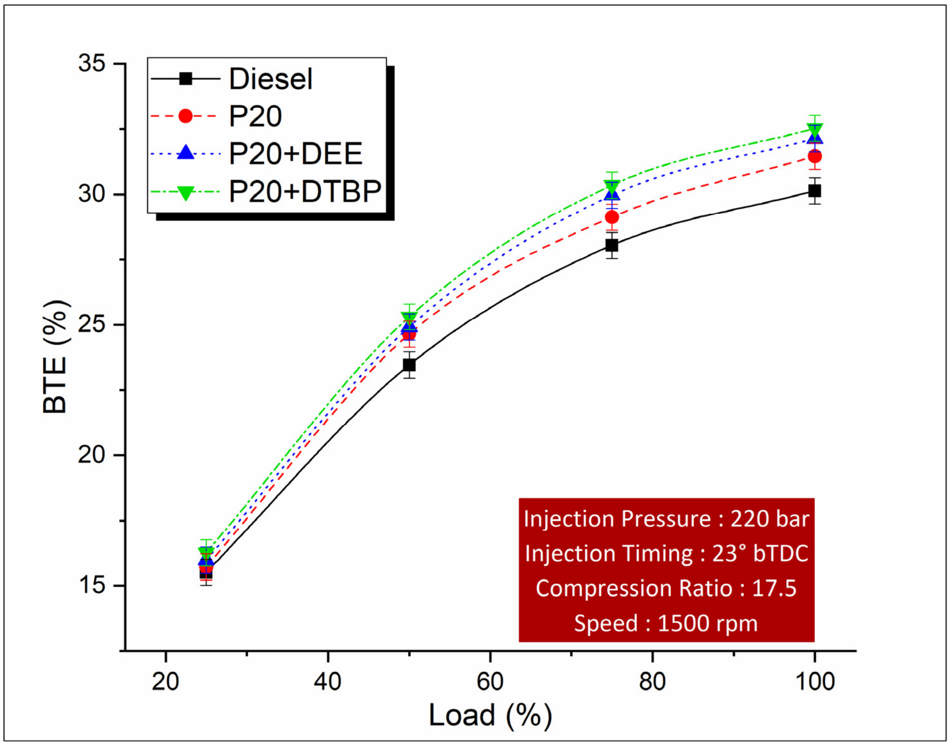


Figure 6. BTE variation for test fuel blends at different load condition.

3.3. Emission Analysis

This section presents the results that quantify the emissions produced from the engine, such as carbon monoxide (CO), unburned hydrocarbon (UBHC), nitrogen oxides (NOx) and Smoke.

3.3.1. Carbon Monoxide

Since the diesel engine is operated in a lean mixture range, its CO emission is considerably lower. Usually, the cylinder's temperature, oxidation rate and the fuel spray pattern influence the CO formation [37]. From Figure 7 it is understood that CO emission for P20 was higher than diesel fuel at low loads and reduced at higher loads. The main reason might be that the oxidation rate will be lower at low temperatures due to delayed combustion onset, and that CO emission is formed due to the insufficient oxygen molecules; the inherent oxygen concentration in the biofuel and the additives also play a vital role in the reduction in CO emission [38]. Thus, CO emission is reduced with the usage of peppermint bio oil. Compared to diesel, CO emission was reduced by 11.9% and 18.57% when DEE and DTBP are added with P20; however, P20 + DEE has significantly less impact than DTBP. The higher latent heat of vaporization property of DEE makes the blend produce more CO than DTBP. This is because the higher latent heat of vapourisation induces a cooling effect inside the combustion chamber [39]; this affects the combustion itself and results in higher CO emission in the exhaust. Combustion initiation was advanced to be noticed for P20 + DTBP blends causing complete combustion, leading to a further CO emission reduction.

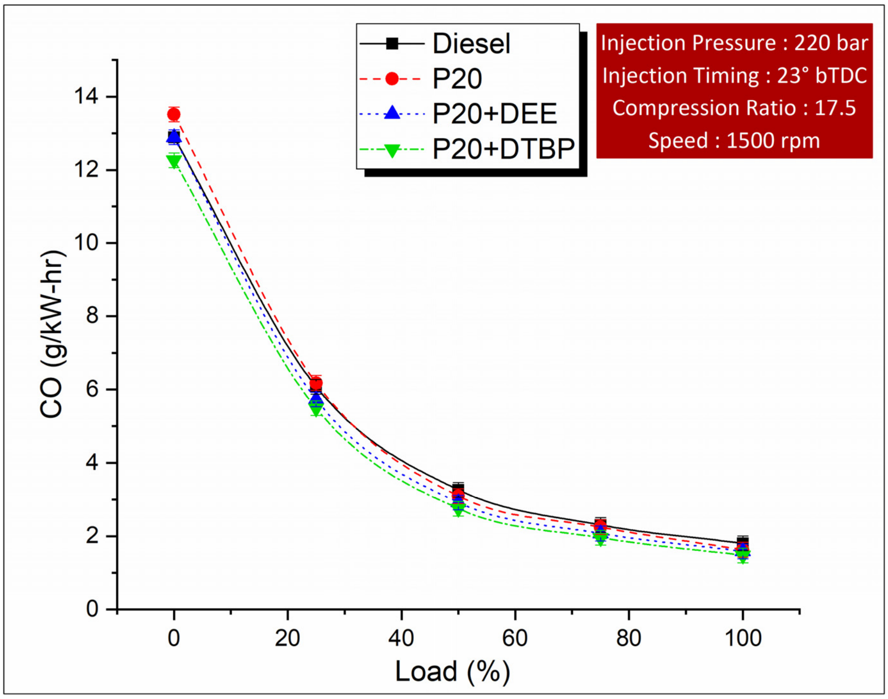


Figure 7. CO variation for test fuel blends at different load condition.

3.3.2. Unburnt Hydrocarbon

Unburned hydrocarbon emissions or simply hydrocarbon emissions are the fuel molecules that escape to the atmosphere without taking part in the combustion process. From Figure 8, it is to be noted that UBHC emission for the P20 + DTBP blend was lower among all fuel blends. With the addition of DTBP to the P20, the blend's combustion quality improves, leading to a decrease in the ignition delay. It promotes the prior onset of ignition, giving more time for oxidation and improved combustion, thus contributing to HC emission reduction. The addition of DEE reduces HC emission by 11.54% and 24.5% more than P20 and diesel fuel, respectively. This is due to the improvements caused in the oxygen concentration, boiling point, viscosity and cetane value of the blend. However, HC emission for P20 + DEE blend was higher than P20 + DTBP blend by 17.95%. This increase in HC emission is due to the reduced in-cylinder temperature caused by the cooling effect of DEE's higher latent heat property. This HC emission reduction was comparable with the results of Samuel et al. for diesel pine oil blends with the addition of cetane improver 1,4 dioxane [40]. HC emission was reduced for P20 + DTBP blend by 35.49% and 24.33% at full load condition compared to diesel and P20 blend.

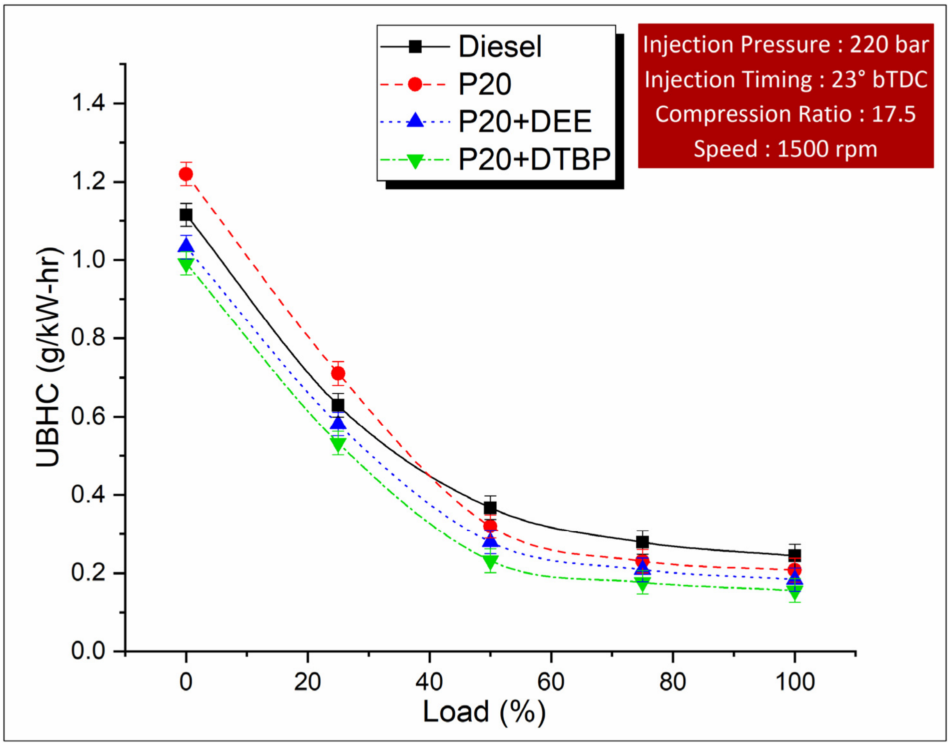


Figure 8. HC variation for test fuel blends at different load condition.

3.3.3. Nitrogen Oxides

Nitrogen oxides is the combination of two toxic gases such as nitric oxide (NO) and nitrogen dioxide (NO_2). These two gases are formed by the combination of nitrogen and oxygen at higher temperatures inside the combustion chamber. Previous studies indicate that low cetane fuels such as Pine oil, Eucalyptus oil, and Methanol emit higher NO_X emission when blended with diesel [10,20,41]. The primary cause for this increase in NO_X emission is higher peak HRR. In conformity with this, P20 diesel blends produce 10.16% (at full load) higher NO_X emission than diesel, as shown in Figure 9. With the addition of DEE in P20 blends, NO_X emission was reduced by 2.33% compared to P20 blend. The primary cause for reducing the NO_X emission was DEE's cooling effect due to its high latent heat property [42]. These results are well in accordance with the work by Paul et al. for diesel DEE blends [26]. Though NO_X emission was reduced for the P20 + DTBP blend compared with P20 blend, it is slightly higher than that of the P20 + DEE blend by 1.14% at full load. The addition of DTBP reduces the ignition delay, leading to a fall in peak heat release rate, causing an overall reduction in cylinder temperature, thereby contributing to NO_X reduction compared to diesel and P20 blend. At full load condition, nitrogen oxides emission is reduced by 10.4 and 9.8% for P20 + DEE and P20 + DTBP blends, respectively, compared to the P20 blend.

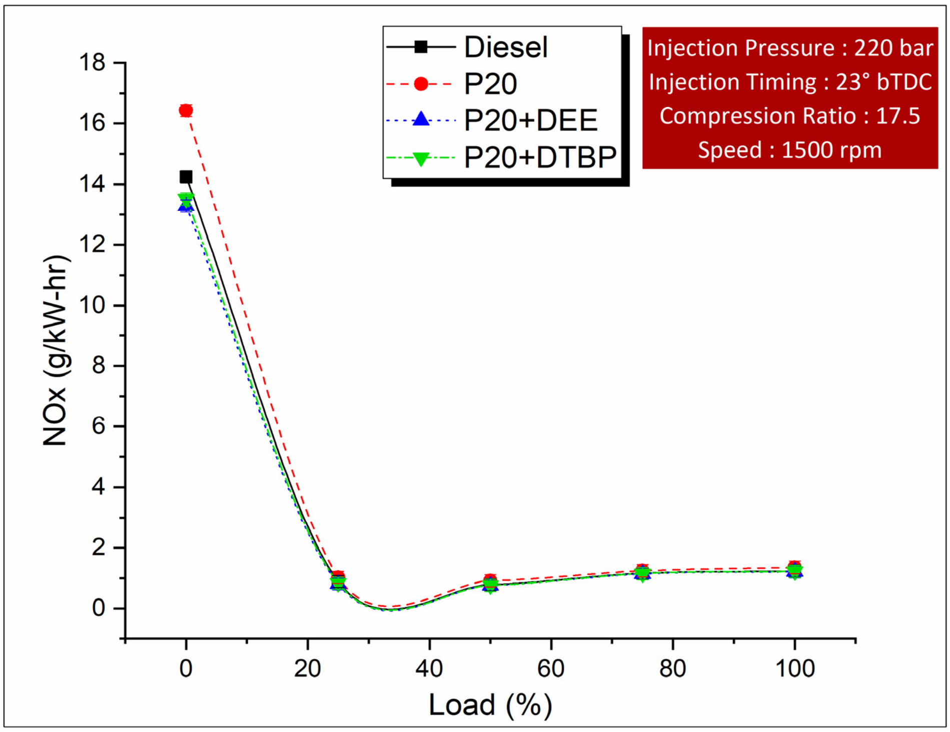


Figure 9. NO_x variation for test fuel blends at different load condition.

3.3.4. Smoke

Figure 10 indicates smoke emission for all the blends in comparison with diesel fuel at different load values. The addition of peppermint oil with diesel fuel improves the oxygen concentration and atomization due to its lower viscosity nature. This helps in better vaporization of the fuel molecules and improves the combustion process, leading to an increased temperature inside the combustion chamber. This helps in better oxidation of soot and reduces smoke considerably compared to diesel fuel [43]. Smoke emission was further reduced by adding DEE with P20 blend. This is due to the increased oxygen contribution, cetane value and reduced viscosity by di-ethyl ether additive, further improving the combustion resulting in better soot oxidation and reduced smoke emission [44]. The smoke emission for the P20 + DTBP blend is only slightly lesser than the P20 + DEE blend. The addition of DTBP to P20 blend increases the premixed combustion phase and contributes to reducing the smoke emission. At full load condition, smoke emission is reduced by 7%, 10.58% and 12.6% for P20, P20 + DEE and P20 + DTBP, respectively, compared to diesel fuel.

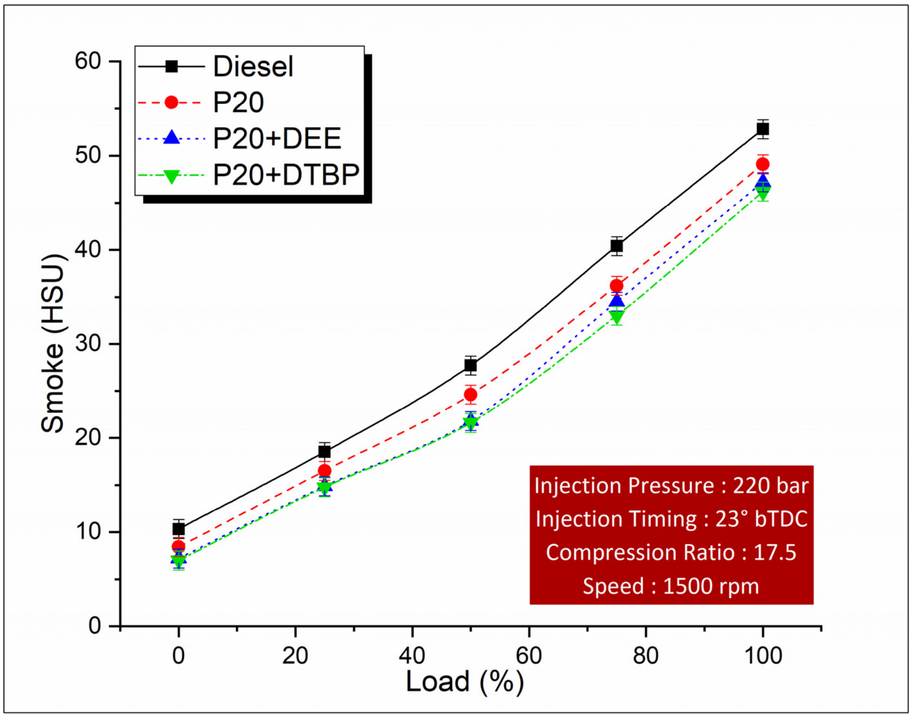


Figure 10. Smoke variation for test fuel blends at full load condition.

4. Conclusions

This study intends to investigate the scope of using peppermint oil influenced by two cetane improver additives in a single-cylinder diesel engine. The following outcomes were observed in this study.

- The peak HRR and NO_X emission were higher for P20 blends than diesel due to reduced cetane number, but CO, HC and smoke emissions were reduced significantly.
- The peak HRR was reduced with the addition of cetane improver DTBP and DEE in the P20 blend. The NO_X emission was reduced by 10.4% and 9.8% for P20 + DEE and P20 + DTBP blends compared to P20 blend due to reduced peak HRR. Improved NO_X emission reduction was observed for P20 + DEE due to its higher latent heat.
- Compared with diesel, P20 + DTBP blend shows improved reduction in CO, HC and Smoke emissions by 18.57%, 35.49% and 12.6% at full load condition.
- The performance characteristic such as BTE and BSFC were improved when compared with P20 blends.

With cetane improvers, 20% peppermint oil can be a potential alternative fuel for diesel engines and we hope to increase the biofuel percentage in the future. The major advantages in the obtained results are the reduction in the level of nitrogen oxides emission, smoke emission, fuel consumption and the improvement in thermal efficiency. Additionally, this approach can ensure that the fuel blends used in this study can be adopted in most of the engines without the need for any major modifications. Moreover, the usage of biofuels means the reduction in carbon dioxide emission during the overall life cycle analysis starting from the crop plantation to the exhaust emitted from the engine, thereby contributing towards the reduction in greenhouse gases in the long run.

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Nomenclature

BDC	Bottom Dead Center
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CAD	Crank Angle Degree
CD	Combustion Duration
CI	Compression Ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Cylinder Pressure
DEE	Di Ethyl Ether
DI	Direct Injection
DTBP	Di Tertiary Butyl Peroxide
EHN	Ethyl Hexyl Nitrate
HC	Hydro Carbon
HRR	Heat Release Rate
IAN	Iso Amyl Nitrate
ID	Ignition Delay
NOx	Nitrogen Oxides
ROHR	Rate of Heat Release
RPM	Rotations Per Minute
SOC	Start of Combustion
SOI	Start of Injection
TDC	Top Dead Center
UBHC	Un-Burnt Hydro Carbon

References

1. Duda, K.; Wierzbicki, S.; Śmieja, M.; Mikulski, M. Comparison of performance and emissions of a CRDI diesel engine fuelled with biodiesel of different origin. *Fuel* **2018**, *212*, 202–222. [CrossRef]
2. Ho, D.P.; Ngo, H.H.; Guo, W. A mini review on renewable sources for biofuel. *Bioresour. Technol.* **2014**, *169*, 742–749. [CrossRef]
3. Poumanyvong, P.; Kaneko, S. Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. *Ecol. Econ.* **2010**, *70*, 434–444. [CrossRef]
4. Duda, K.; Wierzbicki, S.; Mikulski, M.; Konieczny, Ł.; Łazarz, B.; Letuń-Łątka, M. Emissions from a Medium-duty Crdi Engine Fuelled with Diesel-Biodiesel Blends. *Transp. Probl. Int. Sci. J.* **2021**, *16*. [CrossRef]
5. Hunicz, J.; Beidl, C.; Knost, F.; Münz, M.; Runkel, J.; Mikulski, M. Injection Strategy and EGR Optimization on a Viscosity-Improved Vegetable Oil Blend Suitable for Modern Compression Ignition Engines. *SAE Tech. Pap.* **2020**, *3*, 419–427. [CrossRef]
6. Hunicz, J.; Matijošius, J.; Rimkus, A.; Kilikevičius, A.; Kordos, P.; Mikulski, M. Efficient hydrotreated vegetable oil combustion under partially premixed conditions with heavy exhaust gas recirculation. *Fuel* **2020**, *268*. [CrossRef]
7. Panithasan, M.S.; Gopalakichenin, D.; Venkadesan, G.; Malairajan, M. Evaluating the working characters of a diesel engine fueled with biodiesel blends added with rice husk Nano particles. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**. [CrossRef]
8. Abomohra, A.E.F.; El-Sheekh, M.; Hanelt, D. Screening of marine microalgae isolated from the hypersaline Bardawil lagoon for biodiesel feedstock. *Renew. Energy* **2017**, *101*, 1266–1272. [CrossRef]
9. Gnanamoorthi, V.; Devaradjane, G. Effect of compression ratio on the performance, combustion and emission of di diesel engine fueled with ethanol e Diesel blend. *J. Energy Inst.* **2015**, *88*. [CrossRef]
10. Emiroğlu, A.O.; Şen, M. Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine. *Fuel* **2018**, *212*, 34–40. [CrossRef]
11. Ileri, E. Experimental study of 2-ethylhexyl nitrate effects on engine performance and exhaust emissions of a diesel engine fueled with n-butanol or 1-pentanol diesel-sunflower oil blends. *Energy Convers. Manag.* **2016**, *118*, 320–330. [CrossRef]

12. Rakopoulos, C.D.; Rakopoulos, D.C.; Kosmadakis, G.M.; Papagiannakis, R.G. Experimental comparative assessment of butanol or ethanol diesel-fuel extenders impact on combustion features, cyclic irregularity, and regulated emissions balance in heavy-duty diesel engine. *Energy* **2019**, *174*, 1145–1157. [CrossRef]
13. Saxena, M.R.; Maurya, R.K. *Performance, Combustion, and Emissions Characteristics of Conventional Diesel Engine Using Butanol Blends*; Springer: Singapore, 2018; pp. 93–110.
14. Ambrosewicz-Walacik, M.; Wierzbicki, S.; Mikulski, M.; Podciborski, T. Ternary fuel mixture of diesel, rapeseed oil and tyre pyrolytic oil suitable for modern CRDI engines. *Transport* **2018**, *33*, 727–740. [CrossRef]
15. Nanthagopal, K.; Ashok, B.; Saravanan, B.; Pathy, M.R.; Sahil, G.; Ramesh, A.; Nabi, N.; Rasul, M.G. Study on decanol and Calophyllum Inophyllum biodiesel as ternary blends in CI engine. *Fuel* **2019**, *239*, 862–873. [CrossRef]
16. Aguado-Deblas, L.; Estevez, R.; Hidalgo-Carrillo, J.; Bautista, F.M.; Luna, C.; Calero, J.; Posadillo, A.; Romero, A.A.; Luna, D. Outlook for Direct Use of Sunflower and Castor Oils as Biofuels in Compression Ignition Diesel Engines, Being Part of Diesel/Ethyl Acetate/Straight Vegetable Oil Triple Blends. *Energies* **2020**, *13*, 4836. [CrossRef]
17. Mikulski, M.; Ambrosewicz-Walacik, M.; Duda, K.; Hunicz, J. Performance and emission characterization of a common-rail compression-ignition engine fuelled with ternary mixtures of rapeseed oil, pyrolytic oil and diesel. *Renew. Energy* **2020**, *148*. [CrossRef]
18. Vallinayagam, R.; Vedharaj, S.; Yang, W.M.; Lee, P.S.; Chua, K.J.E.; Chou, S.K. Combustion performance and emission characteristics study of pine oil in a diesel engine. *Energy* **2013**, *57*, 344–351. [CrossRef]
19. Panithasan, M.S.; Gopalakichenin, D.; Venkadesan, G.; Veeraraagavan, S. Impact of rice husk nanoparticle on the performance and emission aspects of a diesel engine running on blends of pine oil-diesel. *Environ. Sci. Pollut. Res.* **2019**, *26*. [CrossRef]
20. Devan, P.K.; Mahalakshmi, N.V. An experimental investigation on performance and emission characteristics of eucalyptus oil-diesel blends in a D.I. diesel engine. *SAE Tech. Pap. Ser.* **2008**. [CrossRef]
21. Chandra Sekhar, S.; Karuppasamy, K.; Vedaraman, N.; Kabeel, A.; Sathyamurthy, R.; Elkelawy, M.; Bastawissi, H.A.E. Biodiesel production process optimization from Pithecellobium dulce seed oil: Performance, combustion, and emission analysis on compression ignition engine fuelled with diesel/biodiesel blends. *Energy Convers. Manag.* **2018**, *161*, 141–154. [CrossRef]
22. Mebin Samuel, P.; Gnanamoorthi, V.; Purushothaman, P.; Gurusamy, A.; Devaradjane, G. Prediction efficiency of artificial neural network for CRDI engine output parameters. *Transp. Eng.* **2021**, *3*, 100041. [CrossRef]
23. Subrahmanyam, J.P.; Iranmanesh, M.; Babu, M.K.G. Potential of Diethyl ether as supplementary fuel to improve combustion and emission characteristics of diesel engines. In Proceedings of the Fifth International SAE India Mobility Conference on Emerging Automotive Technologies Global and Indian Perspective, New Delhi, India, 9 January 2008. [CrossRef]
24. Li, R.; Wang, Z.; Ni, P.; Zhao, Y.; Li, M.; Li, L. Effects of cetane number improvers on the performance of diesel engine fuelled with methanol/biodiesel blend. *Fuel* **2014**, *128*, 180–187. [CrossRef]
25. Vallinayagam, R.; Vedharaj, S.; Yang, W.; Saravanan, C.; Lee, P.; Chua, K.; Chou, S. Impact of ignition promoting additives on the characteristics of a diesel engine powered by pine oil-diesel blend. *Fuel* **2014**, *117*, 278–285. [CrossRef]
26. Paul, A.; Panua, R.S.; Debroy, D.; Bose, P.K. Effect of diethyl ether and ethanol on performance, combustion, and emission of single-cylinder compression ignition engine. *Int. J. Ambient Energy* **2017**, *38*, 2–13. [CrossRef]
27. Zhang, Q.; Yao, M.; Luo, J.; Chen, H.; Zhang, X. Diesel engine combustion and emissions of 2,5-dimethylfuran-diesel blends with 2-ethylhexyl nitrate addition. *Fuel* **2013**, *111*, 887–891. [CrossRef]
28. Subramanian, T.; Varuvel, E.G.; Ganapathy, S.; Vedharaj, S.; Vallinayagam, R. Role of fuel additives on reduction of NOX emission from a diesel engine powered by camphor oil biofuel. *Environ. Sci. Pollut. Res.* **2018**, *25*, 15368–15377. [CrossRef] [PubMed]
29. Purushothaman, K.; Nagarajan, G. Performance, emission and combustion characteristics of a compression ignition engine operating on neat orange oil. *Renew. Energy* **2009**, *34*, 242–245. [CrossRef]
30. Purushothaman, P.; Gnanamoorthi, V.; Gurusamy, A. Performance combustion and emission characteristics of novel biofuel peppermint oil in diesel engine. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 8547–8556. [CrossRef]
31. Samuel, M.; Gobalakichenin, D.; Gnanamoorthi, V. Assessing the Combined Outcome of Rice Husk Nano Additive and Water Injection Method on the Performance, Emission and Combustion Characters of the Low Viscous Pine Oil in a Diesel Engine. *SAE Tech. Pap.* **2019**, 1–14. [CrossRef]
32. Heywood, J.B. Combustion in Compression Ignition Engines. In *Internal Combustion Engine Fundamentals*; McGraw-Hill Education: New York, NY, USA, 1988.
33. Duh, Y.-S.; Kao, C.-S.; Lee, W.-L.W. Chemical kinetics on thermal decompositions of di-tert-butyl peroxide studied by calorimetry An overview. *J. Therm. Anal. Calorim.* **2017**, *127*, 1071–1087. [CrossRef]
34. Panithasan, M.S. Exploring the Preparation and Usage of Low Viscous Pine Oil and Rice Husk Nano Additives in a CRDI Engine under the Effect of Water Emulsion. In Proceedings of the SAE Powertrains, Fuels & Lubricants Meeting, Krakow, Poland, 22 September 2020. [CrossRef]
35. Ibrahim, A. An experimental study on using diethyl ether in a diesel engine operated with diesel-biodiesel fuel blend. *Eng. Sci. Technol. Int. J.* **2018**, *21*, 1024–1033. [CrossRef]
36. Gurusamy, A.; Gnanamoorthi, V.; Purushothaman, P.; Mebin Samuel, P.; Muhammad Irfan, A.A. Evaluation of Microalgae Biodiesel Blend Along with DTBP as an Ignition Enhancer on Diesel Engine Attributes. In Proceedings of the International Conference on Design, Materials, Cryogenics and Constructions (ICDMC 2019), Chennai, India, 28–29 March 2019.

37. Venu, H.; Madhavan, V. FuInfluence of diethyl ether (DEE) addition in ethanol-biodiesel-diesel (EBD) and methanol-biodiesel-diesel (MBD) blends in a diesel engine. *Fuel* **2017**, *189*, 377–390. [CrossRef]
38. Özener, O.; Yüksek, L.; Ergenç, A.T.; Özkan, M. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel* **2014**, *115*. [CrossRef]
39. Edwin Geo, V.; Nagarajan, G.; Nagalingam, B.; Aloui, F.; Tazerout, M. A comparative analysis of different methods to improve the performance of rubber seed oil fuelled compression ignition engine. *Fuel* **2020**, *280*. [CrossRef]
40. Mebin Samuel, P.; Devaradjane, G.; Gnanamoorthi, V. Performance enhancement and emission reduction by using pine oil blends in a diesel engine influenced by 1, 4-dioxane. *Int. J. Environ. Sci. Technol.* **2020**, *17*. [CrossRef]
41. Mebin Samuel, P.; Devaradjane, G.D.; Venkadesan, G.; Josan, S. Emission Reduction of a Diesel Engine Fueled with Blends of Biofuel under the Influence of 1,4-Dioxane and Rice Husk Nano Particle. *SAE Tech. Pap.* **2019**, 1–8. [CrossRef]
42. Smigins, R.; Zakis, A. Impact of Diethyl Ether/Rapeseed Oil Blends on Performance and Emissions of a Light-Duty Diesel Vehicle. *Energies* **2020**, *13*, 3788. [CrossRef]
43. Gavhane, R.S.; Kate, A.; Soudagar, M.; Wakchaure, V.; Balgude, S.; Fattah, I.R.; Nik-Ghazali, N.-N.; Fayaz, H.; Khan, T.; Mujtaba, M.; et al. Influence of Silica Nano-Additives on Performance and Emission Characteristics of Soybean Biodiesel Fuelled Diesel Engine. *Energies* **2021**, *14*, 1489. [CrossRef]
44. Aguado-Deblas, L.; Hidalgo-Carrillo, J.; Bautista, F.M.; Luna, D.; Luna, C.; Calero, J.; Posadillo, A.; Romero, A.A.; Estevez, R. Diethyl Ether as an Oxygenated Additive for Fossil Diesel/Vegetable Oil Blends: Evaluation of Performance and Emission Quality of Triple Blends on a Diesel Engine. *Energies* **2020**, *13*, 1542. [CrossRef]