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**Premixed charge combustion in a diesel engine fuelled with biodiesel, n-butanol, and ignition improver blends**Gangeya Srinivasu Goteti<sup>1,\*</sup> and Tamilselvan Palsami<sup>1</sup><sup>1</sup>School of Mechanical Engineering, VIT University, Chennai, India\*Corresponding author: [gangeyasrinivasu.2016@vitstudent.ac.in](mailto:gangeyasrinivasu.2016@vitstudent.ac.in)

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**Abstract**

The research aims to achieve optimised combustion by utilising the benefits of both spark ignition engine (SI) and compression ignition (CI) engine combustion properties. This research focuses primarily on gaining the advantages of maximum thermal efficiency and reduced emissions. This research also investigates the usage of biodiesel and an ignition improver with improved operating conditions by supplying n-butanol with preheated air. The experimental work was first conducted for the development of preliminary data using neat diesel. It was then performed using a blend of *Prosopis juliflora* methyl ester (PJME), diesel, and di-ethyl ether as an additive. This blend consists of PJME 25%, diesel 74%, and di-ethyl ether (DEE) 1% on a volume basis and is named B25DEE1. With this blend, improved brake thermal efficiency and reduced emissions were observed. The experiment was repeated by port injecting n-butanol into the preheated air stream (35°C-40°C) in a proportion of 10% volume to the primary injected fuel. This method was used to achieve premixed charge compression ignition. This combustible mixture was named n-butanol vapours (B25DEE1+NB). The engine performance demonstrated improved brake thermal efficiency as well as lower emissions (HC, CO, smoke, and NO<sub>x</sub>). Additionally, higher in-cylinder pressures 86.6 bar and heat release rates of 49.12 J/°CA were noted.

**Keywords:** *Prosopis juliflora* methyl ester, Ignition improver, Cetane number, Diesel engine, Premixed charge compression ignition

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**1. Introduction**

To decrease fossil fuel consumption, there is a need to focus on alternative fuel usage. The selection of alternative fuels must be based on their availability and biodegradability. Its properties must be closer to those of the diesel, which can allow the utilisation of unmodified diesel engines or with little modification for advanced combustion phenomena. Several researchers found various alternative sources that use alcohol-based fuels and biodiesel compounds. Most of the authors concluded that their research findings had shown the suitability of utilising these alcohol fuels and biodiesels with a considerable reduction in emissions and improved performance and combustion characteristics.

Kumar et al. [1] concluded that biodiesel blended with ethanol and preheated inlet air can decrease CO and HC emissions with advanced injection timings. The experimental investigations were conducted by Krishnamoorthi et al. [2] revealed that utilising biodiesel-diethyl ether blends can decrease NO<sub>x</sub> emissions and also improve BTE in diesel engines. The improved brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) and decreased CO emissions were observed by Senthur et al. [3] by preheating the 20% palm oil and blending it with n-butanol, diesel, and a 2000 mg/L butylated hydroxytoluene (BHT) additive. The blends of n-butanol (15%), gasoline (15%), and diesel increased maximum pressures with decreased ignition delay and NO<sub>x</sub> emissions. However, when compared to diesel, CO emissions and BSFC were higher, as demonstrated by Prakash et al. [4]. Murthy et al. [5] conducted an experimental analysis using a 5% di-ethyl ether (DEE) and H<sub>2</sub>SO<sub>4</sub> solution. This solution was injected into the inlet manifold by high-pressure injection. The engine ran on a palm kernel methyl ester blend. Micro explosions occurred due to the DEE addition. This tendency caused an improvement in the swirl in the combustion chamber and thus reduced the ignition delay period. Tsutsumi et al.

[6] concluded that ignition improvers such as DEE and di-methyl ether (DME), when combined with biodiesel blends in small amounts, can further reduce emissions by increasing the evaporation rate. Utilizing these ignition improvers with biodiesel can improve the cetane number to the required extent. Pugazhvadivu et al. [7] used DEE along with a Pongamia biodiesel blend. The results revealed that DEE additives can decrease emissions like NO<sub>x</sub> and smoke. Polyoxymethylene diethyl ethers were used with n-butanol and diesel blends by Huang et al. [8] to achieve improved thermal efficiency and combustion phenomena.

The above literature concludes that the alternative fuels commonly used by researchers are ethyl or methyl esters of biodiesel and alcohol-based fuels for investigating engine performance, emission, and combustion phenomena. Since these fuels are enriched with oxygen and have good miscibility with diesel, Their chemical composition allows them to be used along with diesel with negligible engine modifications. But by increasing the blending percentage of these alcohols and biodiesels with diesel, they can decrease the cetane index further because their cetane index is very low. Because of their enriched oxygen levels, these fuels can also cause increased fuel consumption in comparison to their output power, as Kalargaris et al. [9] demonstrated. Ignition improvers like DEE and DME can be utilised like cetane number improvers with biodiesel to improve the combustion quality. These ignition improvers can reduce the ignition delay period by allowing spontaneous combustion after injection. They can minimise cold-start problems and reduce emissions like NO<sub>x</sub> and HC because of higher latent heat of vaporisation and oxygen percentages [10]. The properties of these ignition improvers, like a higher cetane number, higher volatility, a high latent heat of vaporization, a lower auto-ignition temperature, and miscibility with diesel, can allow them to be used as fuel additives. This research work primarily concerns the utilisation of n-butanol vapours and biodiesel blends along with ignition improver DEE.

The bio-oxygenated content is available in the alcohol fuels. They also have increased volatility and mixing properties with diesel compared to other fuels. They can also increase the efficiency of combustion as they have a high oxygen percentage [11], an increased rate of evaporation even at low pressures, a calorific value, a cetane index, and are renewable in nature. Biodiesel compounds offer the benefits of being non-toxic and renewable, with no residues of Sendzikiene et al. [12] utilised the combination of rapeseed methyl ester, diesel, and ethanol to improve the oxygen percentage. With an oxygen limit of 19%, the normal operating condition was observed at a speed of 1200 rpm and 42.42N of torque. But by increasing the oxygen limits to 19.5%, decreased torque and rotational speeds were observed. By increasing the oxygen percentage in the fuel to 25.7 percent, the engine was not activated. The reduced NO<sub>x</sub> emission was observed with an increased oxygen percentage in the fuel.

From the above literature survey, it was observed that biodiesels, along with alcohol fuel and ignition improver combinations, can be chosen to increase the oxygen percentage to the required extent. In this present study, the selected qualities of biodiesel *Prosopis juliflora* methyl ester (PJME) are closer to those of diesel. Its seed oil is naturally non-edible. The study is unique in that no combustion evaluations on the use of PJME, n-butanol, DEE, and diesel blends were available.

The seed oil of *Prosopis juliflora* is inedible by nature. *Prosopis juliflora* plant is widely available, and it consists of 44 species throughout the world [13]. The higher the cetane number, oxygen percentage, and heating value of this fuel, the closer it is to diesel, making it a good alternative source for diesel engines. With few or no engine modifications, an alcoholic fuel like n-butanol can be used in conventional compression ignition (CI) engines. Diesel's characteristics are contrasted with n-butanol's and *juliflora* oil methyl esters in Table 1. The fundamental reason for using n-butanol is that it has a higher oxygen percentage, which improves the efficiency of combustion. It also has properties like reduced evaporation pressures, increased heating values, and a high cetane number.

An ignition improver like DEE can improve the combustion quality of biodiesel blends. It can improve the cetane number to the proper extent to maintain smooth engine operation. The ignition lag period can be decreased by adding ignition improvers. They can also minimise the cold-starting problems by improving the diffusion rate. By mixing ignition improvers, NO<sub>x</sub> emissions can be reduced significantly due to their elevated latent heat of evaporation. Their high oxygen content may also induce a decrease in HC and CO emissions.

The main objective of this research is to utilise blends of *Juliflora* biodiesel, n-butanol, and ignition improver. The biodiesel blend was meant to decrease conventional fuel usage. The ignition improver is meant to increase the evaporation rate and cetane index. The n-butanol vapours were used to accelerate the reaction rate by further influencing the oxygen content in the test fuel blend and also to reduce the unburned hydrocarbon and carbon monoxide emissions.

**Table 1** Properties of the test fuel.

Specifications	Diesel	n-butanol	DEE	PJME	B25DEE1	ASTM D6751 Standard for biodiesel
Cetane Index	50	17	>125	49	50.5	47-65
Stoichiometric A/F ratio	14.95	11.17	11.1	12.25	14.24	-
Oxygen (wt %)	0	21.58	21	12	3.21	11
Carbon (wt %)	86.12	64.82	64.86	77	83.62	77
Hydrogen (wt %)	13.87	13.60	13.5	12	13.4	12
Lower Calorific Value (kJ/kg)	43390	33100	33900	39500	42330	~33342
Kinematic Viscosity (cSt) at 40°C	3.9	2.63	0.23	4.90	4.09	4.0-6.0
Density (kg/m <sup>3</sup> ) at 15°C	838	810	713	920	857	874.73

## 2. Materials and methods

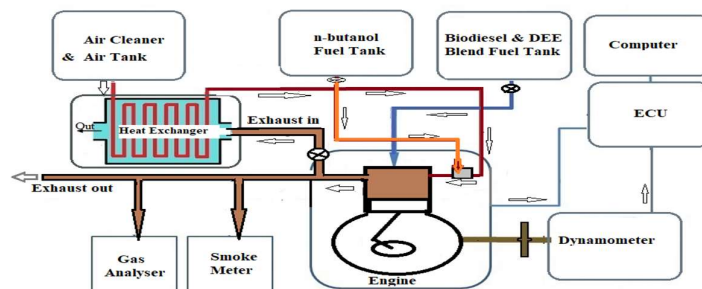
The standards of American society for testing and materials (ASTM) D6751 and EN 14214 are applied for the preparation of biodiesel blends. By adhering to these guidelines, the test fuels were prepared by maintaining the blend density below 860 kg/m<sup>3</sup>, the kinematic viscosity below 4.1 cSt, and the heating value of the blends above 35 MJ/kg.

The test fuel blend consists of 25% biodiesel and 1% ignition improver DEE (Diethyl Ether) and the remaining diesel on a volume basis and is named B25DEE1 (Juliflora Methyl Ester 25%, Diesel 74%, and DEE 1%). The 25% biodiesel was chosen because it attained a higher brake thermal efficiency in the previous experimental analysis when compared to the 15% biodiesel blend [14]. The ignition improver DEE was chosen due to its higher heating value and cetane index when compared to DME [15].

In the next stage, the n-butanol was port injected into the preheated (35°C-40°C) inlet air stream in a proportion of 10% to the main injected fuel (B25DEE1), and this combustible mixture was named B25DEE1+NB. From no load to maximum load, a compression ratio of 18 was used with the diesel and test fuel blends. The main objective of injecting n-butanol into a preheated air stream is to supply n-butanol in the vapour state into the engine cylinder. This can increase the reaction rate and decrease the physical delay period. This can also make the concept of pre-mixed charge combustion more practicable.

### 2.1 Experimental set up

The test rig is represented schematically in Figure 1. Its technical characteristics are listed in Table 2. The test rig consists of a conventional CI engine coupled to a dynamometer. It was also provided with five gas analyzer and a smoke meter. The experimental setup consists of provisions for measuring combustion-related data and is connected to the data acquisition system. An average value of all the test readings was noted by conducting a series of trials at the stabilised condition of the engine with applied loads. This common rail direct injection (CRDI) variable compression ratio (VCR) engine works with a programmable open electronic control unit (ECU) for diesel injection, a fuel injector, a common rail with rail pressure sensor and pressure regulating valve, a crank position sensor, a fuel pump, and a wiring harness. This setup can be used to perform heat balance and combustion analysis.



**Figure 1** Schematic view of the test rig along with ECU.

**Table 2** Test rig details.

Parameters	Description
Engine	Single Cylinder 4S CI Engine.
Power / Speed	3.5 kW / 1500 rpm
Bore / Stroke / Displacement volume	87.5 mm / 110 mm / 661.5 cm <sup>3</sup>
Compression Ratio	18
Main injection pressure/ timing	300 bar/25° before top dead center (BTDC)
Port injection pressure	3 bars (Regulated)
Port injection method	Single, 355° BTDC
Heat Exchanger (for Air pre-heating)	Shell and Tube type
Gas analyzer	Five gas analyzers (AVL DiGas 444N)
Smoke meter	AVL Smoke meter 437°C
Combustion pressure sensor	PCB Piezotronics, USA, Combustion: Range 350 Bar
Crank angle sensor	Kubler Germany, Resolution 1 Deg, 5500 RPM with top dead center (TDC) pulse.

## 2.2 Analysis of errors and uncertainties

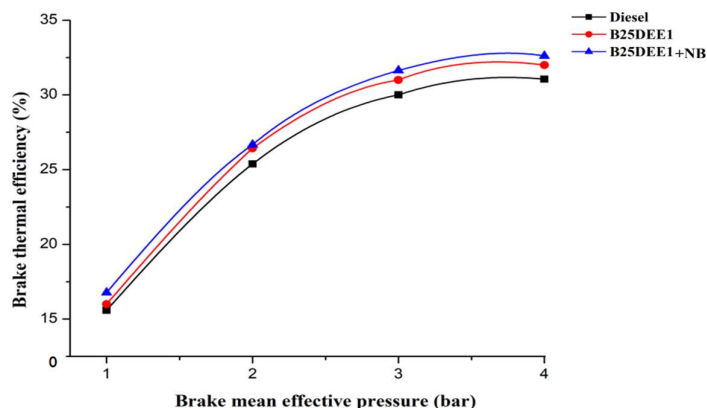
The measured values and uncertainties underwent error analysis using Kline and Mc.Clintock's method [24]. To get results with proper accuracy, the instruments used in this experimental analysis were carefully selected. By evaluating the observed data, it is concluded that the uncertainty values vary between the intervals of  $\pm 0.1$  and 2.0%. Based on the results, it is possible to conclude that the uncertainties in the principle value measurements and derived values have no effect on the numerical result uncertainties.

## 3. Results and discussion

### 3.1 Performance assessment

#### 3.1.1 Brake thermal efficiency

The ratio of the amount of heat actually converted to braking power to the total heat provided is used to calculate this efficiency. Figure 2 depicts the fluctuation of BTE in accordance with brake mean effective pressure (BMEP).



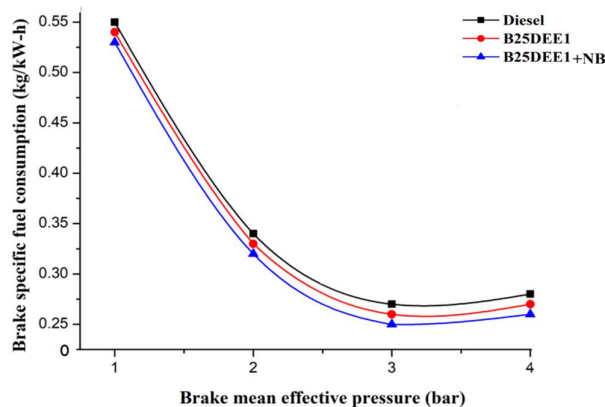
**Figure 2** Brake thermal efficiency versus BMEP.

The BTE for the B25DEE1 test fuel blend was higher than diesel. The increased in-cylinder pressure and temperature at maximum BMEP can cause improved evaporation and mix with air [16]. The addition of DEE also improved and maintained the cetane number to the required extent, and it also improved the oxygen percentage. The BTE was improved further in the following stage by introducing n-butanol vapours with air intake into the cylinder. The test fuel B25DEE1 was mixed with n-butanol vapours in the combustion chamber, and this combustible mixture was named B25DEE1+NB. The improvement in BTE was due to n-butanol vapours. These vapours further improved the evaporation rate and brought the heating values and cetane number closer to diesel. The enhanced cetane number and oxygen percentage in n-butanol vapours and biodiesel blends resulted in improved ignition quality, resulting in a higher BTE. The BTE values for diesel, B25DEE1, and B25DEE1+NB were 31.05%, 32%, and 32.61%, respectively, at full load conditions or at maximum BMEP.

### 3.1.2 Brake specific fuel consumption

This parameter is used to calculate the amount of fuel used in the creation of unit brake power. It also denotes the ability to transfer the fuel's chemical energy into the required work energy. This parameter is influenced by fuel qualities such as oxygen percentage, density, viscosity, and heating values.

From the graph, it is noticeable that as BMEP increased, BSFC decreased. The BSFC for the blend B25DEE1 is slightly higher compared to the combustible mixture B25DEE+NB. The lower heating value of the B25DEE1 blend caused this effect. The reduced BSFC for the combustible mixture B25DEE1+NB was due to the introduction of n-butanol vapours. These n-butanol vapours further influenced the increase in oxygen availability, cetane index, and heating value of the combustible mixture. Figure 3 illustrates the variance of BSFC in relation to BMEP.



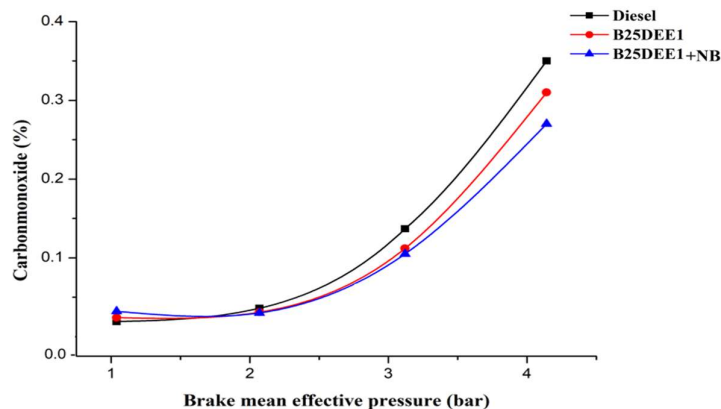
**Figure 3** Brake specific fuel consumption versus BMEP.

The BSFC observed at peak BMEP conditions for diesel, B25DEE1, and B25DEE1+NB was 0.281 kg/kWh, 0.270 kg/kWh, and 0.261 kg/kWh, respectively. The saturated fatty acid content in biodiesel can also influence the cetane number, which is comparable to diesel. The cetane number increases with an increase in saturated fatty acids and an increase in chain length [17]. The PJME saturated fatty acid contents, like palmitic acid and stearic acid, consist of straight-line molecular structures, and their percentage was nearly 23% in PJME [18]. The increased density of the fuel blend is also causing it to inject earlier and providing increased mixing time and evaporation. It can lead to better combustion.

## 3.2 Emission assessment

### 3.2.1 Carbon monoxide analysis

The emission of CO indicates how effectively the combustion process occurred based on the type of fuel utilized. The unburned hydrocarbons influence the formation of this toxic emission. The type of the mixture, oxygen availability, and reaction rates are the influencing parameters for this emission. Figure 4 depicts CO emissions in relation to BMEP. Incomplete combustion, along with rich mixture and heterogeneous mixture combustion with a decreased oxygen percentage, can improve this emission [19]. CO emissions were found to be higher in diesel than in the test blends. Because the biodiesel, n-butanol, and fuel additives used here have a higher oxygen percentage and a lower carbon percentage on a mass basis than diesel. This emission is only slightly less compared to diesel because biodiesel contains increased levels of unsaturated fatty acids. This can lead to the presence of a double bond and influence poor oxidation. This condition can promote increased emissions of carbon monoxide and hydrocarbons [20]. The addition of DEE suppressed this condition to some extent. The addition of n-butanol vapours (B25DEE1+NB) further decreased this emission as it allowed for further improvement in flame propagation [21]. The improvement in flame propagation caused an improvement in reaction rate.



**Figure 4** Carbon monoxide versus BMEP.

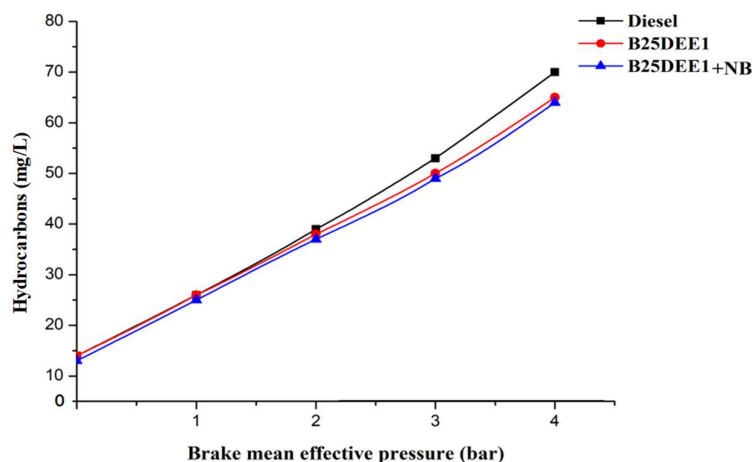
The CO emission at maximum BMEP conditions for diesel, B25DEE1, and B25DEE1+NB was observed at 0.35%, 0.32%, and 0.28%, respectively. The increased CO<sub>2</sub> results were obtained for both test fuels when compared to diesel. When the fuel decomposes at higher temperatures without enough oxygen, a large amount of carbon will be converted into CO instead of CO<sub>2</sub>. The increased oxygen percentages in these fuels led to the conversion of a large quantity of CO into CO<sub>2</sub>. The emissions of CO<sub>2</sub> for diesel, B25DEE1, and B25DEE1+NB were observed at 7.63%, 8.54%, and 8.9%, respectively.

### 3.2.2 Unburnt hydrocarbons analysis

The conditions influencing these emissions are the quality of combustion, fuel atomization, air-fuel mixture, and operating parameters. In Figure 5, the HC emission relative to BMEP is indicated.

The blend strength in the test fuel generally increases the kinematic viscosity and also requires a higher injection pressure. This condition is balanced by adding an ignition improver into the test blend. The increased presence of oxygen and cetane number in the DEE led to an improvement in the combustion process, which in turn decreased the HC emission. When comparing B25DEE1+NB to B25DEE1, there was no significant difference observed for this emission. The HC emissions were not decreased in a considerable manner after adding n-butanol vapours because the improvement in volatility led the air to be overly mixed with n-butanol vapours. This is considered one of the reasons for its ignorable reduction.

The emission of HC may increase if n-butanol is directly injected into the cylinder in liquid form because n-butanol requires a high latent heat of evaporation [22].



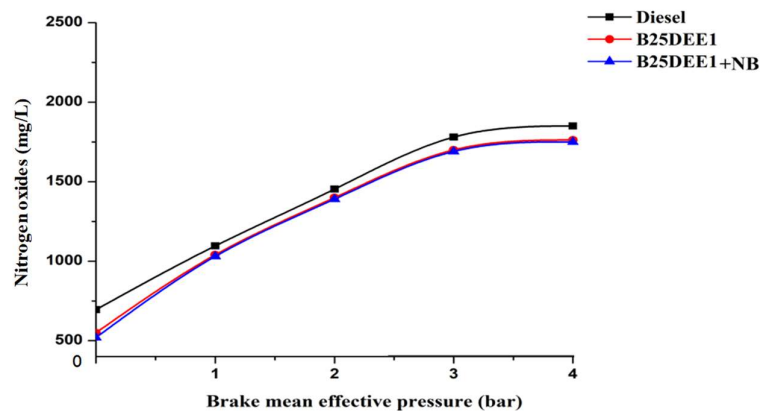
**Figure 5** Hydrocarbon emission versus BMEP.

The emission of HC at peak load conditions, or at maximum BMEP for diesel, B25DEE1, and B25DEE1+NB, was observed at 71 mg/L, 65 mg/L, and 64 mg/L, respectively.

### 3.2.3 Nitrogen oxides analysis

This is the emission that will be produced at higher operating temperatures and the mixture's local stoichiometry. At the highest combustion temperatures and for the longest time at those temperatures, the diatomic nitrogen will be split into monatomic nitrogen. This monatomic nitrogen is highly reactive with oxygen and will produce emissions of NO and NO<sub>2</sub>. With a lower heating value of the blends and a better cetane index, this emission can be reduced. For both the test blends, the addition of DEE has taken place since DEE is an ignition improver and, at higher concentrations, it can improve the high latent heat of vaporisation [23]. This condition can lower in-cylinder temperatures, which can reduce NO<sub>x</sub> formation. The fluctuation of NO<sub>x</sub> emission in relation to BMEP is indicated in Figure 6.

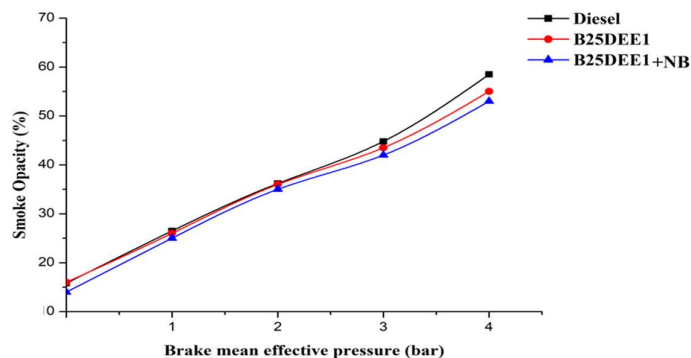
There was no considerable variation between both blends for this emission. These emissions were reduced in a considerable manner compared to diesel. Here, both blends consist of DEE percentages. For the combustible mixture B25DEE1+NB, n-butanol vapours absorbed the most latent heat, resulting in lower NO<sub>x</sub> emissions. The emission of NO<sub>x</sub> at peak load conditions, or at maximum BMEP for diesel, B25DEE1 and B25DEE1+NB, was observed at 1850 mg/L, 1759 mg/L, and 1752 mg/L, respectively.



**Figure 6** Nitrogen oxide emission versus BMEP.

### 3.2.4 Smoke opacity analysis

The emission of smoke increases with improper mixing of fuel with air. Figure 7 shows the amount of smoke produced by the test blends versus diesel. As the compression ratio was increased, smoke opacity was reduced for both test fuel blends in comparison to diesel. The introduction of n-butanol vapours and an ignition improver further improved the mixing process of air with test blends. This emission is also influenced by the hydrocarbon ratio and the effectiveness of combustion. As the hydrocarbon ratio is higher for n-butanol in comparison to diesel, it causes lower smoke emissions [24]. This is one of the reasons considered for B25DEE1+NB's reduced smoke emissions when compared to diesel. By encouraging premixed combustion prior to TDC, this emission can be controlled. The premixed combustion phase was improved by utilising n-butanol vapors. This reduction in smoke opacity was also due to higher oxygen percentages in both blends, which resulted in the maximum quantity of carbon to burn. The smoke emission at maximum BMEP for diesel, B25DEE1, and B25DEE1+NB was observed at 57.8%, 53%, and 51%, respectively.



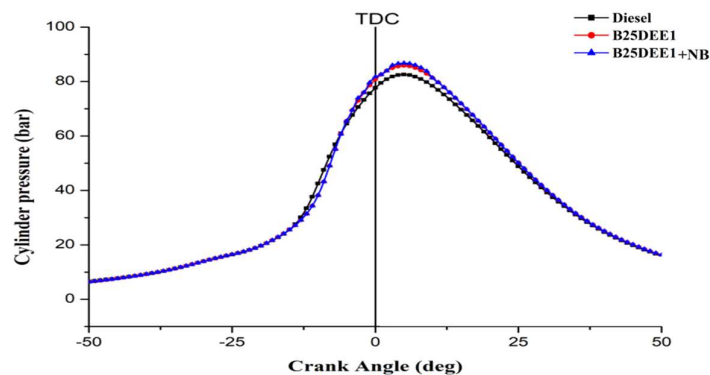
**Figure 7** Smoke emission versus BMEP.

### 3.3 Combustion assessment

#### 3.3.1 In-cylinder pressure analysis

The in-cylinder pressure or gas pressure is affected by the combustion characteristics of the test fuel, as well as the engine's operating parameters. The power output of the engine depends directly on in-cylinder pressure. The combustion phenomenon affects this pressure, which resulted from the fuel's early uncontrolled combustion period [24]. The pre-mixed combustion process occurred after a constant-volume endothermic process. It was also considered one of the causes of peak cylinder pressure with rapid combustion. The constant-pressure endothermic process was also considered diffusion combustion. The fluctuation of in-cylinder pressure with relation to crank angle at maximum BMEP is shown in Figure 8. For the test blends compared to diesel, the maximum in-cylinder pressures were marginally higher. The maximum cylinder pressure was observed for B25DEE1+NB, followed by B25DEE1 and diesel. Both blends had strong peak pressures soon after TDC, demonstrating that, unlike diesel, combustion did not deviate from its regular pattern.

The peak pressure obtained was the result of uncontrolled combustion, oxygen percentage in blends, and calorific value. The availability of oxygen in both DEE and biodiesel, as well as the heating value of biodiesel, which is closer to diesel, were considered impacting parameters for improved cylinder pressure in B25DEE1. The combustible mixture formation increased these pressures further after the addition of n-butanol vapors. The cylinder pressure reached its maximum when combustion began due to a large amount of fuel burned.



**Figure 8** Cylinder pressure versus crank angle.

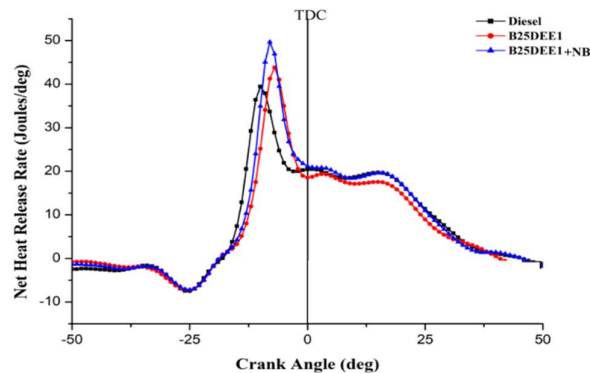
With more fuel being used during peak times, the working temperature and evaporation rates increased. They could also be a contributing factor to higher cylinder pressures in both test fuels. The peak pressure obtained was 80 bar when fueled with diesel and for B25DEE1, B25DEE1+NB it was 84.7 bar and 86.6 bar respectively.

#### 3.3.2 Heat release rate analysis

A thorough investigation of the combustion methodology is possible with this evaluation of rate of heat release. The net heat release rate can be influenced by operating conditions as well as fuel characteristics. It results from the heat energy that the fuel's chemical energy releases, and it will be enhanced by the fuel-air mixture's rapid burning.

This rapid burning can cause maximum net heat release (NHR) because of the fuel accumulation during the ignition lag period. The variation of NHR in relation to the crank angle at maximum BMEP is shown in Figure 9. The elevated NHR was observed for B25DEE1 compared to diesel because of the accumulation of more fuel during the ignition delay period, which caused a rapid rate of combustion. One of the factors for ignition delay was the increased viscosity of the blend, which affects the physical delay period. The chemical lag period can be influenced by the percentage of oxygen present. The B25DEE1 blend's oxygen level caused it to produce the most NHR compared to diesel. The preheated air can also influence the physical delay period [25]. For the B25DEE1+NB combustible mixture, the NHR was further increased with increased oxygen availability. To some extent, the addition of DEE improved cetane number and evaporation rate. The premixed combustion can also utilise the maximum quantity of vaporised fuel at the end of the ignition delay period. The premixed combustion intensity depends upon the time available for the formation of the combustible air-fuel mixture. Due to this characteristic, both blends performed better than diesel in terms of maximum cylinder pressure and NHR. For all fuels close to 25° BTDC, negative NHR was discovered due to heat absorption during the fuel evaporation phase or the ignition delay phase. The maximum heat release rate (HRR) found for both blends at 6° BTDC. It was observed as 46.5 J/°CA and 49.12 J/°CA for B25DEE1 and B25DEE1+NB, respectively. The maximum HRR for diesel was found at 8° BTDC at 39.38 J/°CA.



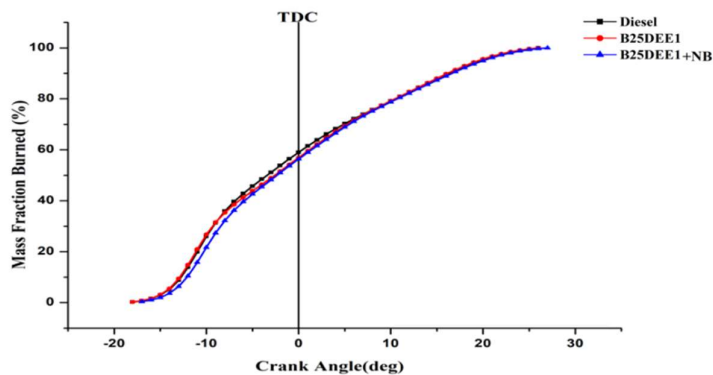


**Figure 9** Net heat release rate versus crank angle.

### 3.3.3 Mass fraction of the fuel burned

The time interval between the initiation of the flame and uncontrolled combustion could be measured by utilising this parameter. This also shows the percentage of fuel consumed in relation to the total quantity of fuel supplied into the combustion chamber per cycle. This is also used to calculate the time between the commencement of the flame and the quick rate of combustion [26].

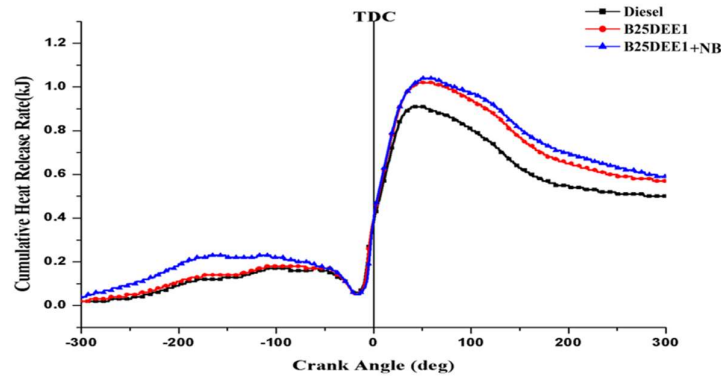
In comparison to diesel, there was no combustion delay in the early stages of premixed combustion for both test fuel blends. The operating temperatures increased as the n-butanol vapours were added. As a result, the B25DEE1+NB blend's volatility and flame speed became compatible with diesel. The mass fraction burnt (MFB) for both blends compared to diesel is shown in Figure 10. The mass percentage of fuel burned exactly like diesel for both blends at the same crank angle. The mass fraction of the fuel burned near TDC for diesel, B25DEE1, and B25DEE1+NB was 54%, 53.10%, and 53.62%, respectively.



**Figure 10** Mass fraction of fuel burned versus crank angle.

### 3.3.4 Cumulative heat release analysis

It provides information regarding the heat energy obtained by the chemical energy of the fuel. It also indicates the quality of the combustion. Figure 11 indicates the variation of the cumulative heat release rate with crank angle. From the start of the combustion process onward, the test blends followed the same pattern as a standard curve for diesel, but the blend B25DEE1+NB showed a higher cumulative heat release (CHR) when compared to diesel as the combustion process progressed. The rapid rate of combustion of this blend was due to the higher amount of oxygen in it [27]. The ignition delay period could also be regarded as a contributing factor to the rapid rate of combustion that influenced maximum CHR for test blends rather than diesel. The maximum CHR was observed at 0.92 kJ, 1.01 kJ, and 1.05 kJ for diesel, B25DEE1, and B25DEE1+NB, respectively.



**Figure 11** Cumulative heat release versus crank angle.

#### 4. Conclusion

The experimental work for both test fuel blends has obtained the following statements when compared to diesel at maximum BMEP conditions. The higher BTEs were observed for both test blends because of increased oxygen percentages and an improved combustion strategy. The cetane index and oxygen contents were also increased to the required extent with the addition of DEE. The emissions of CO, HC, smoke, and NO<sub>x</sub> for both test fuel blends were slightly reduced. The in-cylinder pressures were higher immediately after TDC, revealing that both test fuel blends had no unusual combustion behaviour in comparison to a diesel with a crank angle, and no unusual pressure rise was observed. Increased maximum cylinder pressures were observed for both test fuel blends. The combustion process was normal, and no considerable abnormalities were observed. Due to its minimal vaporisation pressures and quick burning process, the introduction of n-butanol vapours resulted in high peak pressures as compared to diesel. The NHR observed was higher for the test fuel blends compared to diesel. This study also comes to the conclusion that because both test fuel blends had higher viscosities than diesel, higher injection pressures were needed for them.

All of the preceding has demonstrated that n-butanol vapours, along with biodiesel and DEE, can be added to diesel in modest amounts to reduce conventional diesel fuel use and pollutants. Additionally, it enhances a premixed-charged compression ignition (PCCI's) combustion phenomenon for CI engines.

#### 5. References

- [1] Kumar KS, Raj RTK. Effect of fuel injection timing and elevated intake air temperature on the combustion and emission characteristics of dual fuel operated diesel engine. *Procedia Eng.* 2013;64:1191-1198.
- [2] Krishnamoorthi M, Malayalamurthi R. Availability analysis, performance, combustion and emission behavior of bael oil - diesel - diethyl ether blends in a variable compression ratio diesel engine. *Renew Energy.* 2018;119:235-252.
- [3] Senthur PS, Asokan MA, Prathiba S, Ahmed S, Puthan G. Effect of additives on combustion, performance and emission behaviour of pre heated palm oil/diesel blends in DI diesel engine. *Renew Energy.* 2018;122:196-205.
- [4] Prakash T, Edvin GV, Leenus JM, Nagalingam B. Effect of ternary blends of bio ethanol, diesel and castor oil on performance, emission and combustion in a CI engine. *Renew Energy.* 2018;122:301-309.
- [5] Satyanarayana Murthy YVV. Performance of tobacco oil-based bio- diesel fuel in a single cylinder direct injection engine. *Int J Phys Sci.* 2010;5(13):2066-2074.
- [6] Tsutsumi Y, Iijima A, Yoshida K, Shoji H, Lee JT. Combustion characteristics during operation on DME and methane fuels. *Int J Automot Technol.* 2009;10(6):645-652.
- [7] Pugazhvadivu M, Sankaranarayanan G. Investigations on a diesel engine fuelled with biodiesel blends and diethyl ether as an additive. *Indian J Sci Technol.* 2009;2(5):31-35.
- [8] Huang H, Liu Q, Teng W, Pan M, Liu C, Wang Q. Improvement of combustion performance and emissions in diesel engines by fueling n-butanol/diesel/PODE3-4 mixtures. *Appl Energy.* 2018;227:38-48.
- [9] Ioannis K, Guohong T, Sai G. Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil. *Fuel Process Technol.* 2017;157:108-115.
- [10] Byungchul C, Xiaolong J, Young KK, Gilsung J, Chunhwan L, Inchul C, Chi SS. Effect of diesel fuel blend with n-butanol on the emission of a turbocharged common rail direct injection diesel engine. *Appl Energy.* 2015;146:20-28.

- [11] Tamilselvan P, Nagarajan G. Combustion and emission characteristics of a diesel engine fuelled with biodiesel having varying palmitic acid, stearic acid and oleic acid in their fuel composition. *Int J Oil, Gas and Coal Technol.* 2014;8(3):353-368.
- [12] Sendzikiene E, Makareviciene V, Janulis P. Influence of fuel oxygen content on diesel engine exhaust emissions. *Renew Energy.* 2006;31(15):2505-2512.
- [13] Patnaik P, Abbasi T, Abbasi SA. *Prosopis (Prosopis juliflora): blessing and bane.* *Trop Ecol.* 2017;58(3):455-483.
- [14] Tamilselvan P, Goteti GS. Experimental analysis of VCR engine operated with prosopis juliflora biodiesel blends. *Int J Renew Energy Res.* 2020;10:978-987.
- [15] Goteti GS, Tamilselvan P. HCCI combustion in a diesel engine using oxygenated fuels and various operating parameters. *Int J Renew Energy Res.* 2017;7:1166-1173.
- [16] Savariraj S, Ganapathy T, Saravanan CG. Performance and emission characteristics of diesel engine using high-viscous vegetable oil. *Int J Ambient Energy.* 2012;33(4):193-203.
- [17] Mohebbi M, Reyhanian M, Hosseini V, Muhamad Said MF, Aziz AA. Performance and emissions of a reactivity controlled light-duty diesel engine fueled with n-butanol-diesel and gasoline. *Appl Therm Eng.* 2018;134:214-228.
- [18] Rajeshwaran M, Raja K, Marimuthu P, Duraimurugan MD. Biodiesel production and optimization from *Prosopis julifera* oil – a three step method. *Int J Adv Eng Technol.* 2016;6(2):214-224.
- [19] Tamilselvan P, Goteti GS. Performance, emission and combustion characteristics of VCR CRDI diesel engine fuelled with n-butanol blends. *Int J Automot Mech Eng.* 2019;16(3):6825-6843.
- [20] Tamilselvan P, Nagarajan G. Combustion and emission characteristics of a diesel engine fuelled with biodiesel having varying saturated fatty acid composition. *Int J Green Energy.* 2013;10:952-965.
- [21] Tamilselvan P, Nagarajan G, Sasikumar M. Performance and emission characteristics of a diesel engine using blends of biodiesel by varying saturated fatty acid compositions. *Int J Chemtech Res.* 2016;9(9):508-513.
- [22] Imtenan S, Masjuki HH, Varman M, Varman M, Sajjad H, Arbab MI. Effect of n-butanol and diethyl ether as oxygenated additives on combustion–emission–performance characteristics of a multiple cylinder diesel engine fuelled with diesel–jatropha biodiesel blend. *Energy Convers Manag.* 2015;94:84-94.
- [23] Subbarayan MR, Senthil Kumar JS. A study of performance and emissions of direct injection diesel engine fuelled with cotton seed oil methyl ester and pumpkin seed oil methyl ester and its blends with diesel using exhaust gas recirculation. *Biofuels.* 2015;6:171-177.
- [24] Zehra Ş, Orhan D, Orhan NA. Experimental investigation of n-butanol/diesel fuel blends and n-butanol fumigation-evaluation of engine performance, exhaust emissions, heat release and flammability analysis. *Energy Convers Manag.* 2015;103:778-789.
- [25] Bang-Quan H, Xu C, Chang LL, Hua Z. Combustion characteristics of a gasoline engine with independent intake port injection and direct injection systems for n-butanol and gasoline. *Energy Convers Manag.* 2016;124:556-565.
- [26] Rajesh Kumar B, Saravanan S, Rana D, Nagendran A. A comparative analysis on combustion and emissions of some next generation higher-alcohol/diesel blends in a direct-injection diesel engine. *Energy Convers Manag.* 2016;119:246-256.
- [27] Ahmed IE, Ookawara S. Performance, combustion, and emission characteristics of a diesel engine fueled with Jatropha methyl ester and graphene oxide additives. *Energy Convers Manag.* 2018;166:674-686.