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Research Article

Experimental Investigation into the Combustion, Performance, and Emission Characteristics of Oxygenated DEE and Ethanol Blending with KOME Biodiesel Fuelled CI Engine

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ABSTRACT

The present study aims to develop different strategies for better utilization of oxygenated Diethyl ether and ethanol as supplementary fuels by blending them with biodiesel as the base fuel in CI engines. The used biodiesel used was readily available Karanja Oil Methyl Ester (KOME), its scientific name being Pongamia Pinnata. Initially, 5 %, 10 %, 15 %, and 20 % amounts of ethanol (volume) were mixed with biodiesel. Further, the optimum selected blend BE15 was mixed with 5 %, 10 %, 15 %, and 20 % DEE by volume to make the ternary blend. This DEE-ethanol-biodiesel blend was tested on the same engine under the same conditions. The experimental results exhibited that the DEE-ethanol-biodiesel ternary blend, BE15DE10, mitigated BTE by 8.89 % and the smoke, NOx, and CO emissions by 15.66 %, 50.7 %, and 18.5 %, respectively, compared with neat biodiesel. The HC emission exhibited a slightly increasing trend. The results summarize the trade-off between smoke and NOx reduction using DEE and ethanol oxygenated fuels. The addition of ethanol by 15 % and DEE up to 10 % by volume to biodiesel could be considered the most favorable blend without any significant modifications in the CI engine.

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1. INTRODUCTION

A 'green' move to adopt alternative fuels over conventional petroleum-based fuels such as biodiesel, biogas, ethanol, methanol, DEE, DME, CNG, HCNG, LPG, LNG, hydrogen, propane, and P-series fuels are primarily preferred as an energy source for the transportation sector. Biofuels offer much potential on these frontiers as alternative energy [1, 2]. Vegetable oils fulfill the requirements of an alternative source of energy [3, 4]. Edible oils like Coconut oil, Rapeseed oil, Palm oil, Soyabean oil, Mustard oil, Sunflower oil, Waste cooking oil, and Rice bran oil can be used as biofuels. Also, non-edible oils like Jatropha Curcas oil, Castor oil, Karanja (Pongamia Pinnata) oil, Mahua oil, Canola oil, and Neem oil can be used as biofuels with minor modifications to automotive engines [5, 6].

Biodiesel is a clean alternative fuel produced from vegetable oils and animal fats considered safe and biodegradable [7, 8]. Biodiesel production from edible oil is not economical and non-edible seed like Karanja is less costly and widely available in India. Karanja trees can grow on non-agricultural lands with minimum care [9]. The seeds of Karanja contain 27-39 % of the oil and have the potential to be used as basic feedstock for biodiesel production [10, 11]. Hence, the oil can be easily converted into KOME biodiesel through transesterification or pyrolysis [12]. It can be used as a neat fuel in the CI engines or by blending with diesel fuel. Its reasonable cetane number, almost no sulfur, no aromatics, and about 10 % inherent oxygen reduce harmful emissions [13]. Compared to petroleum diesel, biodiesel suffers from higher viscosity, increased NOx emission, and cold starting problems [14].

Ethanol (CH_3-CH_2-OH) is another promising renewable bio-based and highly oxygenated alternative fuel. Ethanol is derived from biomass by fermenting and distilling the crops. It is a clear, volatile, flammable, and colorless liquid. Its high oxygen content improves emission quality in CI engines and its high-octane level makes it suitable for SI engines. However, CI engine fuel suffers from low cetane value, no ignition features, and inadequate solubility in diesel fuel. In ambient conditions, ethanol blends readily with diesel fuel. At a temperature below 10 °C, ethanol separates from diesel fuel. On the other hand, ethanol and biodiesel can be easily mixed at any ratio and it forms a true solution [15]. The lower viscosity of ethanol than diesel is a concern for lubricity [16].

Diethyl ether (DEE) consists of two ethyl groups that are bonded to central oxygen specified by the chemical formula

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CH_3CH_2-O-CH_2CH_3. DEE has a low autoignition temperature, high cetane number, and high oxygen content. Its energy density, solubility with diesel, and broad flammability limits make it suitable for the CI engine [17, 18]. It appears as a clear colorless, volatile, highly inflammable liquid with an anesthetic odor [19]. DEE is safe because of its broad flammability and ease of handling as it remains liquid under ambient conditions [20, 21]. The acid ether synthesis process is used to produce DEE on a large scale. The properties of test fuels are shown in Table 1.

The blending of oxygenated additives like ethanol or DEE with biodiesel enhances the oxygen percentage of the fuel-air mixture. Ethanol has the potential to reduce soot. While high ignition quality of DEE works as a co-solver and boosts the emission performance when blended with ethanol and KOME biodiesel.

Table 1. Properties of test fuels [22, 23]

Properties	Unit	DEE	Ethanol	KOME Biodiesel	Diesel
Chemical structure	-	CH_3CH_2-O-CH_2CH_3	CH_3-CH_2-OH	C_{12} to C_{22}	C_{10} to C_{25}
Oxygen content	mass %	21.6	34.7	10-12	0
Cetane number	-	>125	8	48-60	40-55
LCV	MJ/kg	33.8	26	38.3	34.9
Density at NTP	kg/m^3	713	785-789	875-885	815-860
Viscosity at NTP	cSt	0.23	1.2	1.9-6	2.4-4.1
Autoignition temp.	℃	160	420	-	316
Boiling point at 1 atm	℃	34.6	78	182-337	180-360
Stoichiometric A/F ratio	mass	11.1	9.06	13.8	14-14.7
Molecular weight	g/mol	74	46	-	-
Flammability limit in the air	vol %	3.4-18.6	4.3-19	-	7.6-1.4

2. EVALUATION OF BLENDED FUEL PROPERTIES

In this work, the used biodiesel was readily available Karanja Oil Methyl Ester (KOME) known by its local Indian name and its scientific name is Pongamia Pinnata. The commercial ethanol of analysis grade has 99.5 % purity and the analytical grade DEE has purity ≥ 99.5 % used in this research work. Different ratios of DEE and ethanol were added as supplementary oxygenated fuels to the base biodiesel fuel. Initially, 5 %, 10 %, 15 %, and 20 % volumes of ethanol were mixed with biodiesel and denoted by BE5, BE10, BE15, and BE20, respectively. The optimum blending ratio of the ethanol-biodiesel blend was found as BE15 considering various performance parameters of combustion and emissions of the test fuels. Then, for further investigation, the optimized blend BE15 was mixed with 5 %, 10 %, 15 %, and 20 % DEE by volume to prepare the ternary blend and they are denoted by BE15DE5, BE15DE10, BE15DE15, and BE15DE20, respectively.

Initially, the solubility of both oxygenated fuels, DEE, and ethanol in the biodiesel was checked, which is the requirement for the stable working of the engine. It was observed that there was no phase separation for many days. This reveals that DEE and ethanol are completely miscible with biodiesel. Various instruments and standard methods used to measure fuel properties are shown in Table 2. As per the standard test method (IS 1448), the properties of test fuels were measured. The properties of test fuels are summarized in Table 3.

Table 2. Standard methods and instruments used to measure properties of blended fuels

Properties	ASTM method	Instrument used
Distillation profile	D86	Distillation apparatus
Higher calorific value	D240	Rajdhani make isothermal bomb calorimeter
Density	D941	Pyknometer, elect balance
Kinematic viscosity	D445	Stevis viscometer

Table 3. Properties of DEE-ethanol-KOME biodiesel blends

Properties/Abbreviations	Unit	Blend fuels							
		BE5	BE10	BE15	BE20	BE15DE5	BE15DE10	BE15DE15	BE15DE20
Oxygen content	mass %	12.07	13.26	14.36	15.64	14.49	15.52	16.02	17.68
HCV	MJ/kg	39.71	39.39	38.37	37.88	38.01	37.86	37.73	37.08
Density at NTP	kg/m^3	878	871.4	865	858.5	860.9	858.7	850.1	841.4
Viscosity at 40 °C	cSt	3.92	3.43	3.14	3.00	2.94	2.36	2.03	1.82

The boiling range characteristics of hydrocarbon fuels are studied by using distillation tests [24]. This study uses the ASTM D86 distillation test method for various ethanol-biodiesel blends. The distillation test results are shown in Figure 1. It is shown that the front-end volatility increases upon the addition of ethanol with biodiesel. The initial boiling point of biodiesel observed is 175 °C. The BE20 blend shows an IBP of 38 °C only. Although it reveals that increase in the ethanol concentration in biodiesel rises the front-end volatility. This effect improves the cold start condition. Consequently, it reduces exhaust emissions at a low load. A considerable change in the tail-end volatility of the ethanol-biodiesel blends was not observed. The studies carried out by Menezes et al. [20] reported similar results.

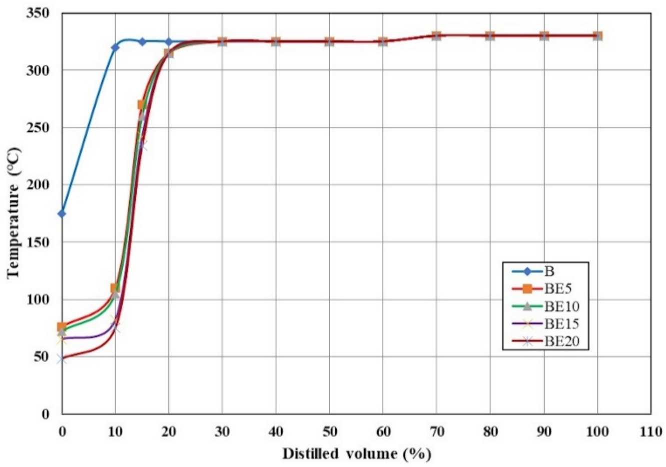

Figure 1. Distillation profile for ethanol-biodiesel blend

The laboratory tests show that the viscosity of the DEE-ethanol-biodiesel blends reduces upon increase in the concentration of ethanol and DEE in it. However, this decreased viscosity is greater than required for CI engines. It reveals that modifications of the fuel injection system are not required. The calorific value and density of DEE-ethanol-biodiesel blends are reduced because of the lower calorific value of ethanol and DEE than biodiesel. The inbound oxygen percentage of the fuel or various blends is an important factor in evaluating the properties of the fuel. It is observed that adding ethanol and DEE increases the oxygen content of blends.

3. EXPERIMENTAL SETUP AND PROCEDURE

In this experimental investigation, the engine test rig was developed with necessary instruments for conducting the experimental tests at a constant speed of 1300 rpm in different brake load conditions. A single-cylinder, four-stroke cycle CI, direct injection, 3.5 kW, 17.5:1 CR, 661 CC engine was used. The engine specifications are tabulated in Table 4. This naturally aspirated, water-cooled, stationary engine is typically used for pump sets in agricultural applications. The injection timing was set to 29° BTDC. The eddy current dynamometer (400 kW) was used for loading the engine. The pressure inside the cylinder was monitored by a piezo sensor. The cooling water was measured using Rota-meter. The TDC and crank angle positions were observed by a Kuebler make crank angle encoder. The data acquisition system was used for collecting various inputs. The multi-gas analyzer, AVL Digas 444, was employed to measure CO, HC, and NO emissions. While the AVL 437 smoke meter was applied to measuring smoke opacity. The RTD and 'K' type thermocouples were used for various temperature measurements. The schematic diagram of the test engine is shown in Figure 2. The accuracies checked of measurement instruments are presented in Table 5.

Table 4. Test engine characteristics

Model	Kirloskar, TV1 Model
Brake power	3.7 kW @ 1300 rpm
Displacement	661 cm^3
Injection timing	29° BTDC
Intake air system	Naturally aspirated
Cylinders	Single cylinder
Comp. ratio	17.5:1
Inj. opening pressure	19.6 MPa
Type	Four-stroke cycle
Combustion System	Diesel direct injection

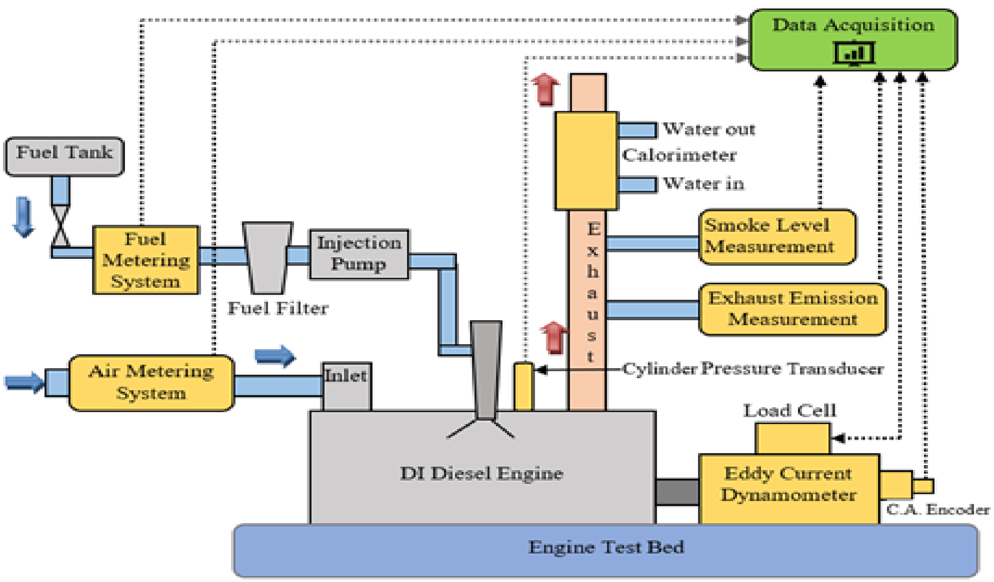

Figure 2. Schematic view of the test engine

Table 5. Accuracies of measurement parameters

Parameters	Measurement unit	Accuracy
Smoke opacity	%	± 1 % FSR
NOx	ppm	± 1
CO	% vol	± 0.01 %
HC	ppm	± 1
CO_2	% vol	± 0.1 %
Speed	rpm	± 0.5 % FSR
Temperature	°C	± 0.1 %
Mass fuel consumption	gm	± 0.01 %
Volumetric fuel consumption	ml	± 1 % FSR
Time	Sec	± 0.01 %
Density	kg/m^3	± 0.2
Calorific value	kJ/kg	± 0.15

The fuel samples were tested in various load conditions: no-load, 25 %, 50 %, 75 % of full load, and full load. These tests were carried out at a rated speed of 1300 rpm. Initially, the engine was run at no load for 30 mins to set in normal conditions. Every test was repeated at least three times for the accuracy of the results. The average values of combustion, performance, and emissions parameters were noted and analyzed.

4. RESULTS AND DISCUSSION

4.1. Combustion characteristics

The combustion in CI engine has two distinct phases of combustion viz. premixed and diffusion phase (mixing controlled) combustion. Once combustion starts, the fuel ignites immediately after injecting it into the cylinder and burns it at the diffusion combustion phase. It leads to a high heat release rate during premixed combustion than diffusion combustion [25]. The combustion characteristics of various DEE and ethanol blends with KOME biodiesel were monitored using in-cylinder pressure trace analysis under steady-state engine conditions. The prominent combustion behaviors such as cylinder pressure and heat release rate were observed at full load; hence, in this condition, the combustion characteristics have been analyzed.

The cylinder pressure for different DEE-ethanol-biodiesel blends is given in Figure 3. The results show that the ignition delay is extended with ethanol-biodiesel blends. This may be because of a reduction in cetane value, increased heat of evaporation, and a high level of auto-ignition temperature. Xin-Cai et al. [26] argued that in the ethanol-biodiesel blend, the biodiesel fuel burns first and then, it ignites the surrounding ethanol. The rise in peak pressure is observed because of an increase in fuel combustion at the premixed combustion phase. One can observe that the peak pressure attained for all the DEE-ethanol-biodiesel blends is moving away from TDC. It can be because of the effect of elongation in ignition delay and retardation of the start of combustion.

The net heat release rate for DEE-ethanol-biodiesel blends is shown in Figure 4. It shows that high HRR at the end of combustion leads to a longer duration of HRR. This is because of the elongated ignition delay of ethanol-biodiesel blends. The combustion start was observed with delay for all DEE blends and with an increase in DEE percentage, it turned into a prominent one. The increase in HRR for the diffusion combustion phase is observed because of oxidation resulting from oxygen concentration in the blends [27].

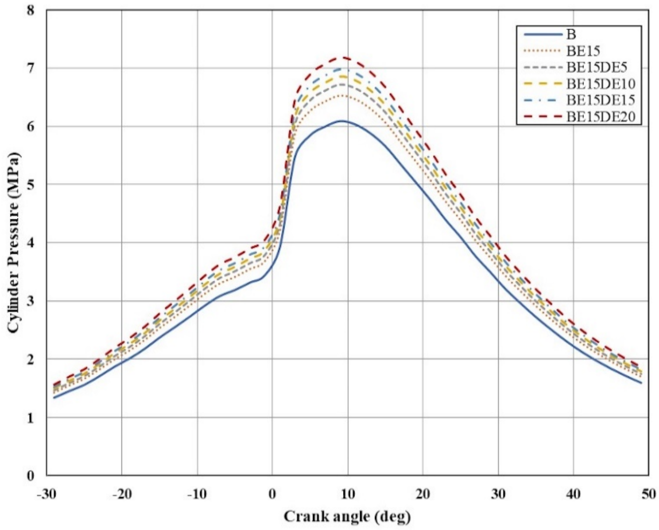

Figure 3. Cylinder pressure variations for DEE-ethanol-biodiesel blends

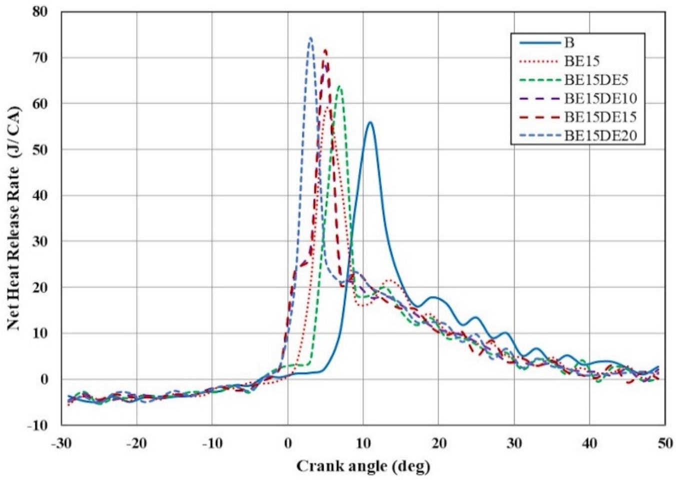

Figure 4. Net HRR variations for DEE-ethanol-biodiesel blends

4.2. Performance characteristics

The brake thermal efficiency assesses the fuel energy conversion efficiency into brake power. The other parameters like BSFC and BSEC have not been discussed in this work because they do not show different results from BTE.

The results of the BTE of ethanol-biodiesel are shown in Figure 5. The BTE increases with the addition of ethanol to biodiesel. The maximum BTE is observed for 15 % ethanol blending with biodiesel (BE15), especially in full-load conditions. This BE15 optimum blend is selected as a base fuel for the second step of the tests. Then, DEE is added to the BE15 blend in different proportions. The BTE for the DEE-ethanol-biodiesel blend is presented in Figure 6. The blending of DEE percentage of more than 15 % in BE15 blends shows the reduction in BTE near full load. The BE15DE10 blend shows maximum BTE than other blends at full load. This improvement in BTE results from fuel-bound oxygen concentration, particularly in the fuel-rich zone [28]. The erratic operation was observed in engine operation when more than 15 % DEE was added to the BE15 blend, thereby affecting the engine performance. It is observed that the BTE of BE15DE10 blend has increased by 8.9 % more than the neat biodiesel fuel.

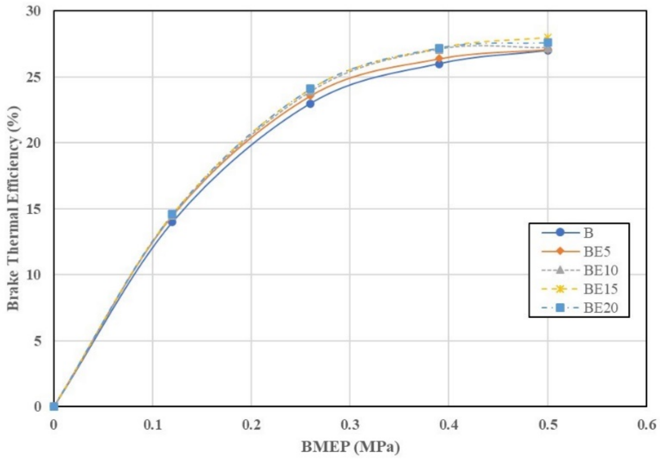

Figure 5. BTE for **e**thanol-biodiesel blends

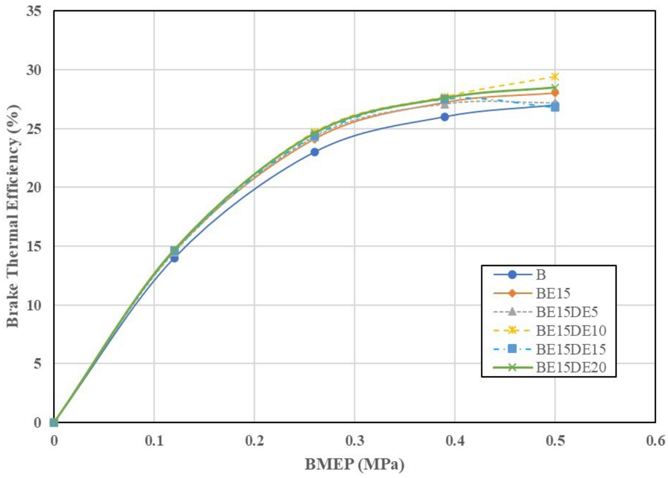

Figure 6. BTE for DEE-ethanol-biodiesel blends

4.3. Emission characteristics

The fuel ignition quality, proper mixing of air and fuel during ignition delay, and residence time lead to the burning of uneven air/fuel mixtures during combustion, and expansion processes have a significant impact on emission formation in diesel or biodiesel engines [25].

4.3.1. Smoke emission

The results of smoke for ethanol-biodiesel blends are given in Figure 7. It exhibits the trend of reduction in smoke by blending ethanol with biodiesel. The fuel-bound oxygen content in ethanol improves combustion quality, especially in diffusion combustion, which improves smoke emission [29]. At low load, the ethanol blends exhibit minor effect on smoke emission. It is because of the engine running at the overall lean mixture and the low flame temperature of the ethanol-biodiesel blends. Overall, the BE15 blend is the optimum blend and shows a smoke reduction of 13.8 % relative to biodiesel fuel.

The effect of DEE blending with BE15 on smoke is shown in Figure 8. The smoke emission reduction with DEE-ethanol-biodiesel blends is not as much as expected. On the other hand, when more than 15 % DEE is added to the BE15 base fuel, a minor increase in smoke emission is observed which may result from erratic combustion, as discussed before. The findings reported by Anand et al. [30] are in line with these results. The DEE-ethanol-biodiesel ternary blends reduced 15.66 % smoke emissions on average, compared to neat biodiesel. The reduction in smoke may be because of the presence of inherent oxygen of DEE and ethanol in the fuel reach zone, which assists the engine to run leaner. The BE15DE15 blend exhibits the lowest smoke emissions overall and at full load condition as compared to other blends.

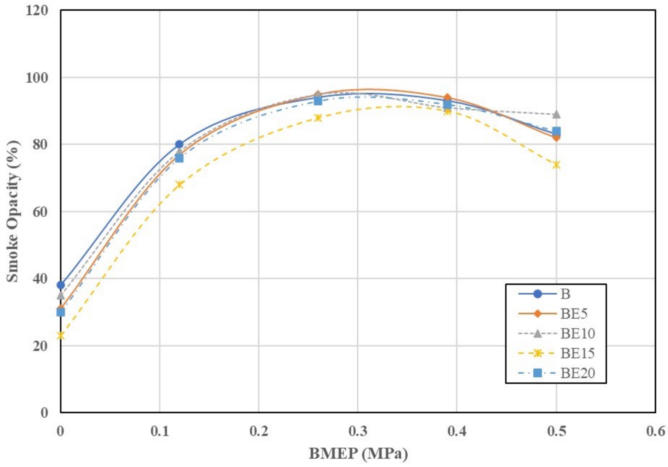

Figure 7. Smoke emission for ethanol-biodiesel blends

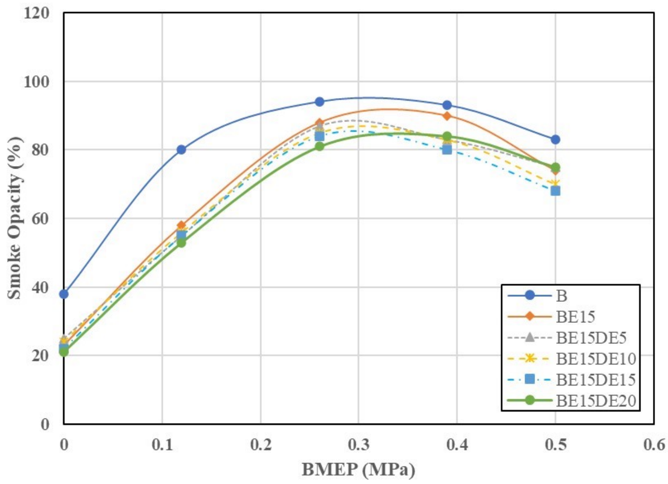

Figure 8. Smoke emission for DEE-ethanol-biodiesel blends

4.3.2. NOx emissions

The NOx produced in diesel or biodiesel engines is proportional to combustion efficiency. The results of NOx emissions of ethanol-biodiesel blends are presented in Figure 9. At high loads, when compared with biodiesel, the NOx emissions exhibit a prominent reduction. The ethanol addition to biodiesel reduces the viscosity and density of blends. Consequently, it retards the dynamic injection timing of the blends. Moreover, as discussed before, it leads to low combustion temperature because of the high evaporation rate of ethanol. These two factors cause a reduction in NOx emissions. It is seen that the NOx emission at lower ethanol ratios is not significant due to the poor ignition quality of ethanol. Overall, the studies reveal that the BE15 blend has the lowest NOx emission at high load.

Further, the DEE blended with the optimum selected blend BE15 and findings are presented in Figure 10. It can be said that there are further reductions in NOx emissions due to blending in the presence of DEE in the blends. The experimental results exhibit that DEE-ethanol-biodiesel ternary blends reduce 50.7 % NOx emissions on average as compared to neat biodiesel. As it is evident, the inherent oxygen of the fuels plays a more active role in the reduction of NOx emission than the oxygen provided by air [31]. The BE15DE20 blend exhibits the lowest NOx emissions and in full-load conditions. A reduction in NOx emission level results from the joint effect of the engine running leaner as well as the lower combustion temperature and reaction time. It is to be noted that the mixture of DEE-diesel blends is effectively leaner with respect to the corresponding neat diesel fuel.

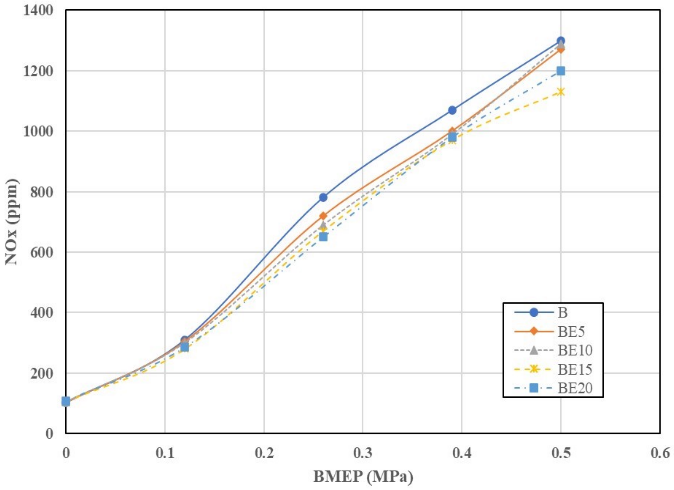

Figure 9. NOx emissions for ethanol-biodiesel blends

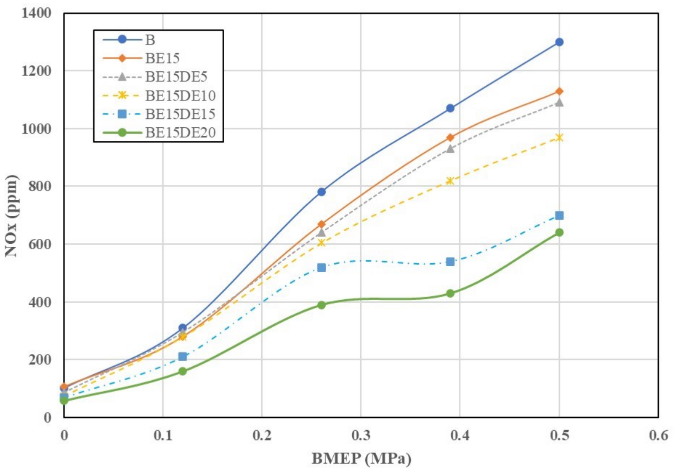

Figure 10. NOx emissions for DEE-ethanol-biodiesel blends

4.3.3. CO emission

The effect of ethanol–biodiesel blends on CO emission is given in Figure 11. The results reveal that the CO emitted by all ethanol-biodiesel blends increased at low loads except for the BE20 blend. At lower loads, the incomplete combustion of the blended fuels increases the CO emission. However, a substantial reduction in the CO emission is observed at full load for all the blends. This effect results from the increase in oxygen concentration of the blends that encourages the additional oxidation of the CO emission during the engine expansion process [32, 33].

The CO emission for the DEE-ethanol-biodiesel blend is presented in Figure 12. Overall, the blend BE15DE10 exhibits further reductions in the CO emission at high load. The experimental investigation exhibits that the CO emission of DEE-ethanol-biodiesel ternary blends is reduced by 18.5 %, compared to neat biodiesel. This effect is attributed to the reduction in density and viscosity of the DEE-ethanol-biodiesel blends and improvement in the start of injection and ignition timing because of the presence of DEE in the blends.

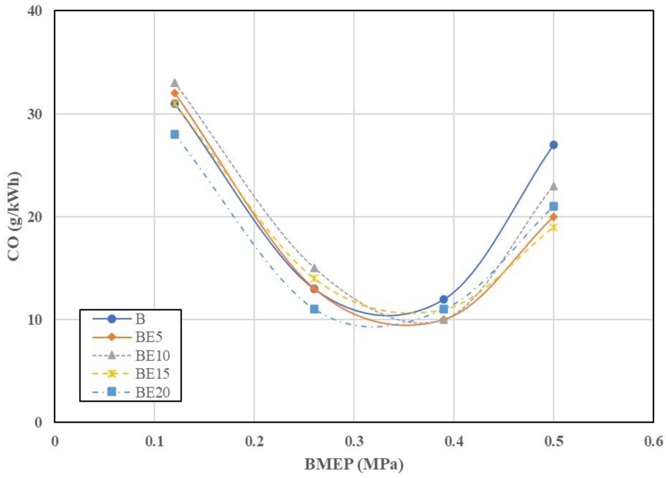

Figure 11. CO emission for ethanol-biodiesel blends

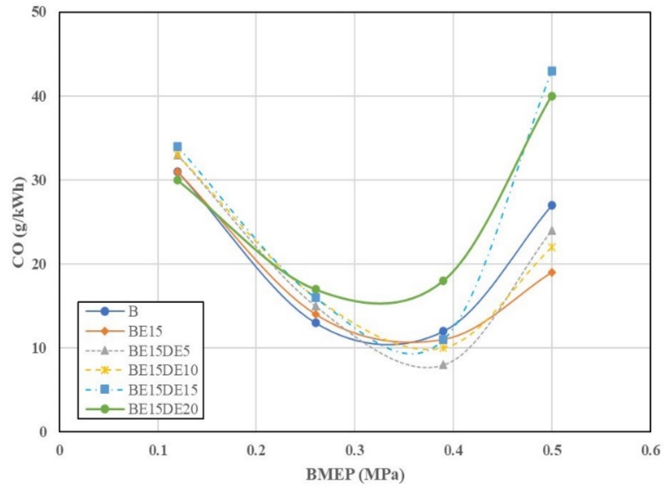

Figure 12. CO emission for DEE-ethanol-biodiesel blends

4.3.4. HC emission

The HC emission for ethanol-biodiesel blends is given in Figure 13. The studies reveal that the HC emission of ethanol-biodiesel blends is increased compared to the biodiesel fuel. Also, the rise in HC emission is observed as the concentration of ethanol in the blend increases. The considerable rise is displayed by HC emission at low loads and it increases moderately at high loads.

The HC emission for DEE-ethanol-biodiesel blends is shown in Figure 14. The outcomes of DEE–ethanol-biodiesel blends reveal that there is a rise in the HC emission for all blends, compared to the BE15 base fuel. At full load, the blend BE15DE10 exhibits the lowest level of HC emission among other DEE-ethanol-biodiesel blends. The HC emission is increased mainly because of higher heat of evaporation of the DEE-ethanol-biodiesel blends causing slower evaporation, which causes poor fuel-air mixing, flame quenching, and the increase of 'lean outer flame zone' where the flame is unable to exist [2].

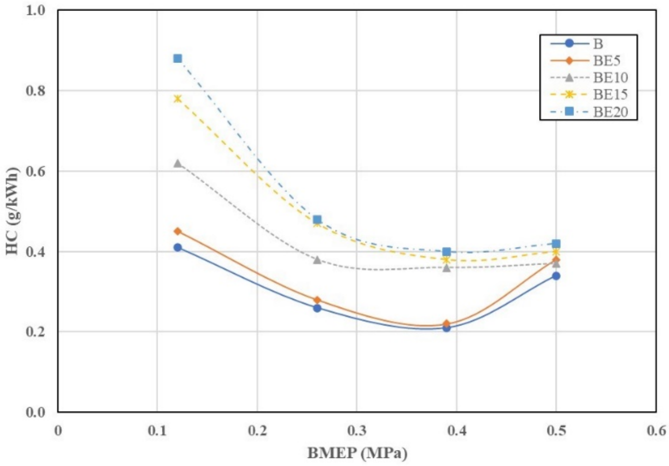

Figure 13. HC emission for Ethanol-Biodiesel blends

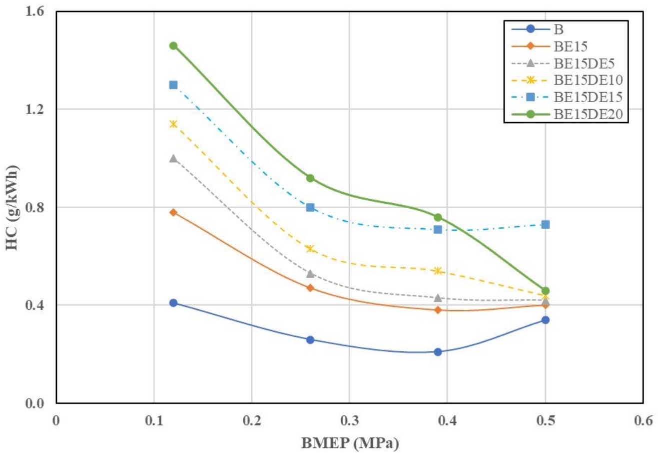

Figure 14. HC emission for DEE blends with BE15

5. CONCLUSIONS

The blending of oxygenated DEE and ethanol into biodiesel changes the physicochemical properties of the blends. The laboratory tests showed that DEE and ethanol remained completely soluble in biodiesel at any ratio. The experimental investigation revealed that the blending of DEE and ethanol with biodiesel up to 20 % by volume was possible. The DEE-ethanol-biodiesel blends resulted in a decrease in density, kinematic viscosity, and higher heating value, whereas the cetane value and oxygen concentration increased. The front-end volatility increased, while the boiling point of ternary blends was reduced compared to neat biodiesel because of the presence of DEE and ethanol. The combustion studies pointed to the increase in ignition delay, peak pressure, and peak HRR of the DEE-ethanol-biodiesel blends. The BE15DE10 ternary blend exhibited an increase in Brake Thermal Efficiency by 8.89 %, reduction in smoke by 15.66 %, drop in NOx by 50.7 %, and decrease in CO emission by 18.5 %, as compared with neat KOME biodiesel. At full load, it exhibited the lowest level of HC emission compared to other DEE-ethanol-biodiesel blends. These results of BE15DE10 are optimum as compared to other blends. Overall, the trade-off between smoke and NOx of biodiesel engines shows a reduction by blending DEE and ethanol with KOME biodiesel fuel. Thus, the BE15DE10 blend is recommended as the optimum blend without significant engine alterations.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

ASTM	American Society for Testing and Materials
BMEP	Brake Mean Effective Pressure
BTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
CA	Crank Angle
CI	Compression-Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
DI	Direct Injection
DEE	Diethyl Ether
DME	Dimethyl Ether
HC	Hydrocarbon
HCNG	Hydrogen CNG
HCV	Higher Calorific Value
HRR	Heat Release Rate
IS	Indian Standards
KOME	Karanja Oil Methyl Ester
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
NO	Nitric Oxide
NOx	Oxides of Nitrogen
NTP	Normal Temp. and Pressure
PM	Particulate Matter
RTD	Resistance Temp. Detector
SI	Spark Ignition

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