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# Assessment of Diesel Engine Performance, Combustion and Emission Characteristics with Supplementation of Neem Oil Methyl Ester Along With EGR

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## ABSTRACT

Biodiesel generated from a variety of non-edible feedstocks has gained widespread acceptance as a limited diesel fuel alternative in compression ignition engines. For the reliable implementation of biodiesel in commercial sectors, its effect on engine combustion, emission, and performance needs to be examined experimentally. In this study, 10% (N10) and 20 % (N20) Neem oil methyl ester (NME) blends were tested in a direct injection 4-stroke single-cylinder diesel engine incorporated with 5% and 10% exhaust gas recirculation (EGR). At maximum load conditions, Brake thermal efficiency (BTE) was found highest for N20 by 7.2%, and also Brake specific energy consumption (BSEC) was reduced by 11.4% for N20 as compared to diesel. Meanwhile, the incorporation of EGR deteriorates the performance parameters for the N20 blend. The results of emission analysis showed that oxides of nitrogen (NOx) increased with the addition of biodiesel whereas the addition of EGR diminished the NOx value for both biodiesel blends at all loading conditions. Unburnt hydrocarbon (UHC), Carbon monoxide (CO), and smoke emissions decreased by 40.6%, 31.2%, and 29.6% for the N20 blend respectively at full load when compared to diesel. Interestingly, when EGR was provided, CO, UHC, and smoke density values are increased for both N10 and N20 blends at all loading conditions, however lower than diesel operation.

## INTRODUCTION

From the early nineteenth century, principal fuels used for transportation have been derived from petroleum. Predicted depletion of fossil fuels shortly and augmented pollution hazards alarmed by health agencies motivate the search for a renewable source of fuel for the transportation sector (Atul & Avinash 2014). Among prime movers in transportation, diesel engines played a major role due to their high thermal efficiency, robustness, and reliability. In this view, various alternative fuel sources like natural gas, hydrogen, and biofuels came into existence in the last few decades to aid the transportation sector in lessening its dependency on petroleum-based fuels and reducing their impact on the environment (Ardebili et al. 2011).

Vegetable oils are renewable and cost-effective alternative fuels. It can be used directly in CI engines owing to its similar properties to that of diesel fuel (Eryılmaz et al. 2014). Some of the major advantages of vegetable oils are their renewability, availability, low toxicity, and biodegradability. Meanwhile using vegetable oils directly in engines affects the performance and combustion attributes due to their high viscosity, high density, and low calorific value. To overcome these setbacks transesterification should be done to convert the fatty acids into methyl esters which in turn enhance the fuel properties. Biodiesel is a blend of alkyl esters of long-chain fatty acids present in oil synthesized via transesterification (Azad et al. 2013, Leung et al. 2010, Borugadda & Goud 2012). Biodiesel can be used directly in engines as well as in blended form without any engine modification. With increased lubricity and high cetane number, running diesel engines on biodiesel could be advantageous in terms of energy security and environmental safety (Canakci 2007, Knothe 2007). On the other hand, biodiesel fuels have poor low-temperature properties and are more susceptible to auto-oxidation during storage (Mohamed et al. 2017).

In emission aspects, biodiesel maintains a closed carbon cycle which reduces global warming. Due to enhanced fuel properties, utilization of biodiesel reduces emissions of particulate matter, CO, and HC accompanied by augmentation of NOx emission. The increase in NOx when using biodiesel was reported due to high in-cylinder temperature prevails during combustion (Sahoo & Das 2009, Srivastava & Verma 2008, Raheman & Ghadge 2007). To overcome the main drawback of using biodiesel i.e. the NOx emission, certain techniques were adopted by researchers. EGR is a reliable technique that can be employed to reduce NOx emission from engines fueled with biodiesel (Zheng et al. 2004, Yu & Shahed 1981).

In the EGR method, a part of exhaust gas from the engine is re-inducted through the inlet manifold to the combustion chamber with a direction and flow regulator valve. EGR displaces a portion of intake oxygen with diluents from the exhaust ($H_2O$ and $CO_2$) to minimize the formation of NOx during combustion. The maximum cylinder temperature is reduced by the diluents due to their specific heat which lowers the rate of combustion (Thangaraja & Kannan 2016, Majewski & Khair 2006). Even though EGR reduces NOx, it increases HC, CO, and soot emissions with deterioration in engine performance (Brehob 2007). The partial displacement of oxygen at intake reduces the excess air ratio and amplifies the ignition delay (ID). This hike in ignition delay aids in the augmentation of fuel in the premixed combustion phase which increases the peak cylinder temperature. Due to the dilution effect, the partial pressure of oxygen concentration will be reduced which in turn affects the NOx formation kinetics (Maiboom et al. 2008). Exhaust gas can be re-routed into the cylinder either externally or internally. Internal recirculation requires complex mechanisms and variable valve timings whereas external recirculation of exhaust gas is achieved with the external plumbing and the pressure difference of exhaust gas compared to intake air (Baert et al. 1999, Kohketsu et al. 1999, Shin et al. 2011).

Many researchers studied the effects on characteristics of diesel engines using biodiesel as a primary fuel. Lin et al. (2007) used biodiesel processed from waste cooking oil and observed that B50 and N20 are the optimal fuel blends. Masjuki et al. (1996) observed improvement in efficiency and emission with biodiesel from preheated palm oil. Sahoo et al. (2009) fueled a three-cylinder tractor engine with Karanja methyl ester blends. The authors observed that BSFC improves with blend concentration and declines with speed. A sharp drop in smoke opacity for biodiesel blends was also been recorded. Mahanta et al. (2006), found that the N20 blend of Karanja biodiesel showed higher BSFC and BTE than diesel for all the loads. Prabhahar et al. (2012), reported that Karanja biodiesel blends recorded high BSFC values than traditional diesel fuel. Sinha and Agarwal (2005) recorded a 1.5-3% improvement in BTE of the diesel engine when powered by rice bran methyl ester blends. Some other authors revealed that the utilization of biodiesel reduces the performance characteristics of the engine which could be attributed to the high viscosity and low heating value of biodiesel fuels (Rizwanul et al. 2013, Jinlin et al. 2011, Jaichandar & Annamalai 2011). Vinay and Raveendra (2015) stated that the BSFC was increased by 10% when 20% of Neem oil was blended with diesel, and also UHC and CO emissions were reduced by 30% and 8% respectively. He also mentioned that EGR addition reduces volumetric efficiency on account of more specific heat of gases.

Spessert et al. (2004), showed that CO emissions for rapeseed methyl ester and diesel were quite similar whereas a slight increase was observed for methyl ester fuel at low loads. Many kinds of literature work report an increase in NOx emission under all loading conditions with biodiesel (Sun et al. 2010, Lapuerta et al. 2008). Ye and Boehman (2012) analyzed the characteristics of combustion of CRDI engines with biodiesel blends. It was observed that retarding the start of injection (SOI) towards TDC boosted the premixed combustion process and also reported that, an increase in injection pressure results in more HRR owing to air-fuel mixing enhancement. Kanda et al. (2005) adopted EGR up to 54% and reported increased HC, CO, and reduced NOx emissions. Das et al. (2015), tried the Homogeneously charged combustion ignition (HCCI) strategy using dual injection and reported a decrease in NOx by 76% and smoke by 40 % with an 80% premixed ratio and 30% EGR. Zhao et al. (2014), experimented on a 2-cylinder diesel engine with EGR varied from 0-27%. The authors observed that increasing EGR leads to an increase in smoke, CO, and HC and a decrease in NOx emission.

Pankaj et al. (2020), studied the CI engine characteristics, cost, and energy when fueled with Roselle, Karanja biodiesel, and its blends. The author observed an increase in BSFC by 4% and 3.2% respectively for 20% of Roselle and 20% of Karanja oil blends. Also observed decrease in CO2 emission with an increase in engine load.

### Remarks of Literature Survey and Novelty

As a result of an extensive literature survey carried out, it is found that a large array of works was conducted by analyzing the diesel engine characteristics by using various biodiesel methyl esters as a supplementary fuel. But to the surprise, very little work has been reported yet on analyzing the effects of EGR percentage on a CI engine fueled with Neem oil methyl ester blends at standard operating conditions without any hardware modification on the engine. The novelty of this present research work lies in analyzing the performance, emission, and combustion characteristics of a direct injection diesel engine fueled with Neem oil methyl ester along with varying EGR rates.

## MATERIALS AND METHODS

### Neem Oil and Its Properties

In India, the distribution of Neem trees is widespread, as also in South Asia. A matured tree can produce 9-90 kg seeds per year whereas each seed contains 27-39% of oil content. In India, around 30,000 tons of Neem oil seeds are traded annually for commercial purposes like soap making, fuel for lamps and drug synthesis, etc. Therefore, Neem oil become a potential source for the production of biodiesel. Because of its pharmaceutical properties, neem oil is also called "Sarva roga nivarani" (medicine for all diseases). Neem seed kernels are pressed in the mechanical press to produce oil. The composition of neem oil is given in Table 1 and Neem seed and oil are shown in Fig. 1.

The physicochemical properties of Neem oil were evaluated by standard test methods preferred by ASTM and given in Table 2.

## Engine Setup and Methodology

From the results, it was found that Neem oil possessed a high acid value of 36 mg KOH.$g^{-1}$. Since the free fatty acid of raw neem oil was found to be higher, the transesterification process cannot be conducted in a single step. So a two-step process comprising acid-catalyzed esterification and base-catalyzed transesterification was carried out to convert oil into a methyl ester (Naik et al. 2008). The obtained biodiesel was tested as per ASTM standards and the results were on par with the prescribed limits of ASTM D6571.

Effects of Neem oil biodiesel blends on diesel engine characteristics were tested on four-stroke single-cylinder engines equipped with an external EGR system. The schematic and Photo of the experimental setup with all instrumentations and EGR setup are depicted in Fig. 2 and Fig. 3. The detailed specifications of the engine rig are mentioned in Table 3.

Two separate tanks were provided for diesel and Neem oil biodiesel blends respectively. A two-way direction control valve is used to switch the fuels from one tank to another. First, the engine was started and allowed to run for 20 minutes to reach a steady-state after which the biodiesel fuel was allowed by using a control valve. Horiba MEXA-584 and AVL 437 smoke meters were used to analyze the exhaust emission. A constant volume of EGR was supplied to the inlet manifold of the engine. The pressure tank employed is used to regulate exhaust pressure pulse and a heat exchanger is provided to cool the charge before recirculating. A control valve was provided at the gas storage tank to ensure accurate EGR flow. A bag filter is employed to filter particulates in the exhaust gas and supply clean gas for EGR. EGR rate is derived as the ratio between the mass flow rate of recirculated exhaust gas and the total mass flow allowed to pass into the engine cylinder. The EGR percentage was set to 5 % and 10% by adjusting the pre-calibrated EGR valve. The engine was steadily loaded in the range of 0%, 10%, 40%, 70%, and 100%. The engine characteristics of N10 and N20 blends were analyzed by incorporating 5% and 10% EGR for both the blends and related to neat diesel fuel. The experiments were repeated thrice, and an average of the value was considered to ensure reliability. The reason for choosing these conditions is that the biodiesel concentration above 20% deteriorates the performance characteristics, and EGR above 10% induces knocking in the engine.

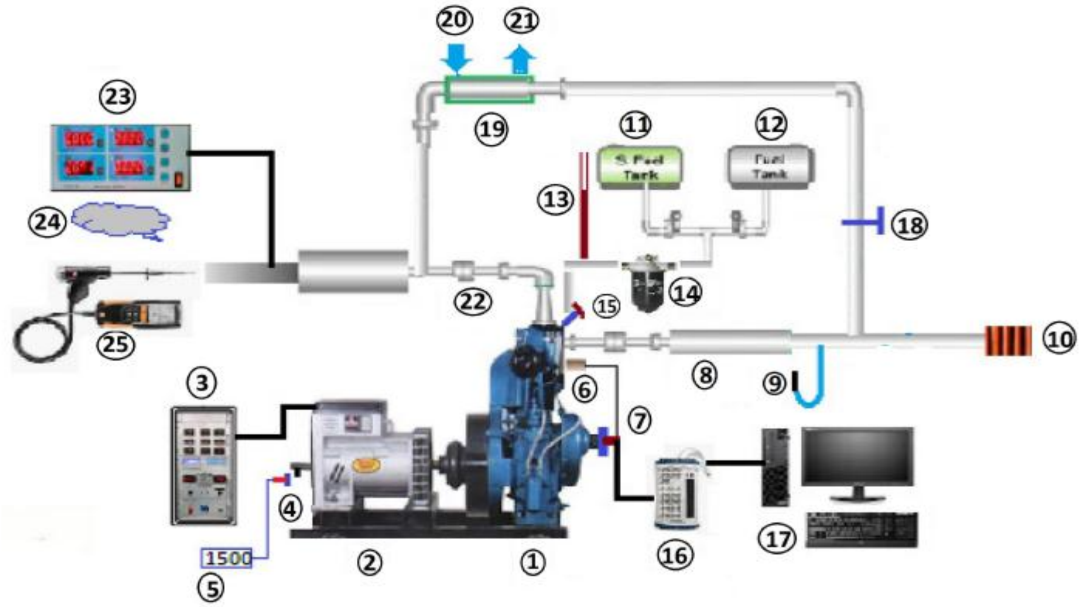
Fig. 1: Neem seed and Neem oil

Table 1: Composition of Neem oil.

| Acid Content | % |
|---|---|
| Olieic | 50-60 |
| Palmitic | 13-15 |
| Stearic | 14-16 |
| Linoleic | 8-16 |
| Arachidic | 1-3 |

Table 2: Physiochemical properties of Neem oil and its methyl ester.

| Property | ASTM method | Prescribed limits | High-speed diesel | Neem oil | Neem oil methyl ester (biodiesel) |
|---|---|---|---|---|---|
| Density ($kgm^{-3}$) | D 1298 | 880 | 850 | 940 | 884 |
| Kinematic viscosity (40°C) ($mm^2 s^{-1}$) | D 445 | 1.9-6.0 | 0.830 | 44 | 4.76 |
| Calorific value (MJ.$kg^{-1}$) | EN 14213 | 35 minimum | 43.5 | 36.85 | 39.65 |
| Acid value (mg KOH $g^{-1}$) | D 664 | 0.5 maximum | 0.2 | 36 | 0.14 |
| Flash point (°C) | D 93 | 130 minimum | 68 | 219 | 135 |
| Cloud point (°C) | D 2500 | -3 to -12 | -11 | 2 | -4 |
| Cetane number | D 613 | 47 minimum | 49 | 39 | 52 |




1 Diesel engine
2 Generator
3 Electrical loading device
4 RPM sensor
5 RPM digital meter
6 Pressure sensor
7 Cam Position sensor and Crank encoder
8 Intake manifold
9 U-Tube manometer
10 Intake air filter
11 Diesel tank 1
12 NME biodiesel tank
13 Burette
14 Diesel filer
15 Diesel fuel injector
16 Data acquisition system
17 Computer
18 EGR valve
19 EGR unit
20 Cooling water in
21 Cooling water out
22 Exhaust manifold
23 Exhaust gas analyser
24 Exhaust gas out
25 Smoke meter

Fig. 2: Experimental setup (schematic).

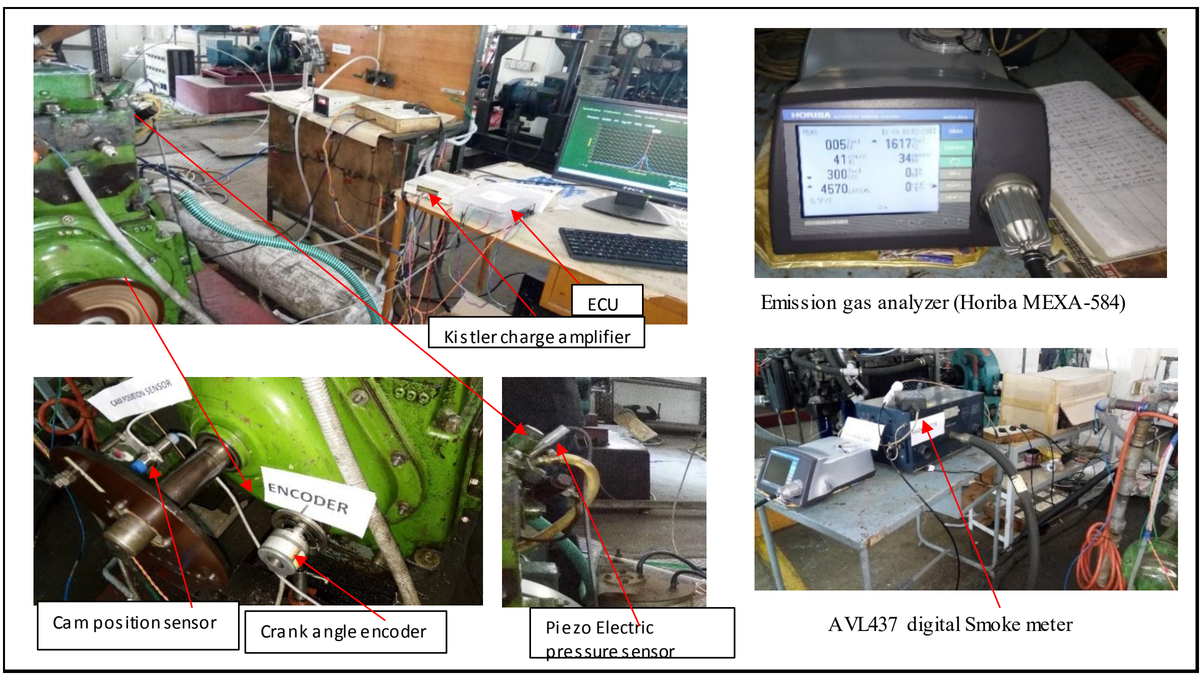



Fig. 3: Experimental setup – Photo.

**Uncertainty Analysis**

All physical quantities are subject to uncertainties. So to ensure reliability and prove accuracy in measurements it is mandatory to carry out uncertainty analysis. Let 'R' be the totaled result function of independent variables x1, x2, x3, $x_n$. (Sakthivel et al. 2016),

$$R = f(x1,x2,x3,.x_n) \quad \dots (1)$$

and measured variables error limits be, x1 ± Δn1 , x2 ± Δn2, …. , xa ± Δna …(2)

and computed result's error limits be R± ΔR. Coleman et al. (2009), described the root mean square technique to understand the degree of error, as

$$\Delta R = [\{(\partial R/\partial x1)^* \Delta x1\}2 + \{(\partial R/\partial x2)^* \Delta x2\}2 + \dots\dots\dots + \{(\partial R/\partial xa)^* \Delta xa\}2 ] \quad \dots(3)$$

Using equation (3), uncertainty in the computed performance and emission parameters were calculated. The details of average uncertainties in experimental measurements are given in Table 4. To calculate the overall uncertainty proportion, the principle of propagation of error is considered and was computed as:

**Overall Uncertainty** = square root of ( uncertainty of fuel flow)$^2$ + square root of ( uncertainty of temperature )$^2$ + square root of (uncertainty of air flow)$^2$ + square root of (uncertainty of EGR flow)$^2$ + square root of (uncertainty of in-cylinder pressure)$^2$ + square root of (uncertainty of crank angle)$^2$ + square root of (uncertainty of CO)$^2$ + square root of (uncertainty of $CO_2$)$^2$ + square root of (uncertainty of NOx)$^2$ + square root of (uncertainty of HC)$^2$ + square root of (uncertainty of smoke)$^2$ + square root of (uncertainty of BTE)$^2$ + square root of (uncertainty of BSFC)$^2$

= square root of $[(0.35)^2+(0.1)^2+(2.2)^2+(1.8)^2+(1)^2+(0.03)^2+(1.8)^2+(0.5)^2+ (2)^2+(1.5)^2+(1.5)^2+(0.07)^2+(0.85)^2]$

= ±4.68%

## RESULTS AND DISCUSSION

### Performance Characteristics

Brake thermal efficiency (BTE) indicates the maximum extent to which the added heat energy is converted to network output. The variations between BTE and brake mean effective pressure (BMEP) is given in Fig. 4. From the figure, it is evident that BTE increases for all test fuels when BMEP increases. At lower engine loading conditions, the biodiesel blends showed lesser BTE than diesel fuel. Reduction in BTE in the order of 2.2 % and 3.4 % was obtained for N10 and N20 blends as compared to diesel at low loading conditions. This diminution in BTE is due to more viscosity and latent heat of vaporization of biodiesel fuel which causes larger droplet formation and insufficient mixing of air-fuel (Qi et al. 2010, Banapurmatha et al. 2008). Meanwhile, at higher loading conditions, the BTE of biodiesel blends showed an increasing trend with diesel. N10 and N20 blends showed a hike of 3.3 % and 7.2 % BTE at full load conditions as compared to mineral diesel. The hike in BTE can be explained by the presence and active participation of oxygen (fuel borne) in fuel which enhances combustion efficiency during higher load conditions. On the other hand, a high engine load help in the mixing and evaporation of biodiesel which in turn increases BTE (Sinha & Agarwal 2005).

At the same time, it can be noticed that the introduction of EGR in the engine deteriorates the BTE of the engine. Incorporating 5% EGR to N10 and N20 blends, decreased BTE by 1.3 % and 1.8% as compared to neat biodiesel operation at low loads. On the other hand, 10% EGR addition to N10 and N20 blends reduced BTE by 1.7% and 4.4% as compared to respective neat biodiesel operations. At high loading conditions, the maximum reduction in BTE was observed for 10% EGR incorporation with N20 which reduced the magnitude of BTE by 3.3 % as compared to neat N20. This reduction in brake thermal efficiency after EGR introduction could be enlightened by the lessening of oxygen available for combustion during the expansion stroke.

Brake-specific energy consumption is defined as the energy of fuel spent to produce unit brake power per hour.

Table 3: The specification of the engine.

| Description | Specifications |
|---|---|
| Make and model | Kirloskar, AV1 |
| Number of cylinders | One |
| Cycle | Four-stroke |
| Cooling | Water-cooled |
| Aspiration | Naturally aspirated |
| Bore and stroke | 80 × 110 mm |
| Swept Volume | 553 cc |
| Clearance volume | 36.87 cc |
| Compression ratio | 16.5: 1 |
| Rated output | 3.7 kW @ 1500 rpm |
| Injection timing | 24° BTDC |
| Combustion chamber | Hemispherical open type |
| Weight of flywheel | 33 kg |
| Lubricating oil | SAE30/SAE 40 |
| Connecting Rod length | 235 mm |
| Valve dia and max lift | 33.7 mm and 10.2 mm |
| Injection nozzle | BOSCH, 3 hole nozzle, 116º spray angle |

Table 4: Uncertainty of the instruments.

| Instruments | Measured parameters | Uncertainty [%] |
|---|---|---|
| Burette | Fuel flow | ±0.35 |
| K-type Thermocouple | Temperature | ±0.1 |
| Flowmeter | Mass flow rate of air | ±2.2 |
| | Mass flow rate of EGR | ±1.8 |
| Pressure sensor (Kistler-6125B) | In-cylinder pressure | ±1 |
| Crank angle encoder | Crank angle | ±0.03 |
| Horiba MEXA gas analyser | CO | ±1.8 |
| | $CO_2$ | ±0.5 |
| | NOx | ±2 |
| | HC | ±1.5 |
| AVL smoke meter | Smoke | ±1.5 |
| Performance parameters | BTE | ±0.07 |
| | BSFC | ±0.85 |

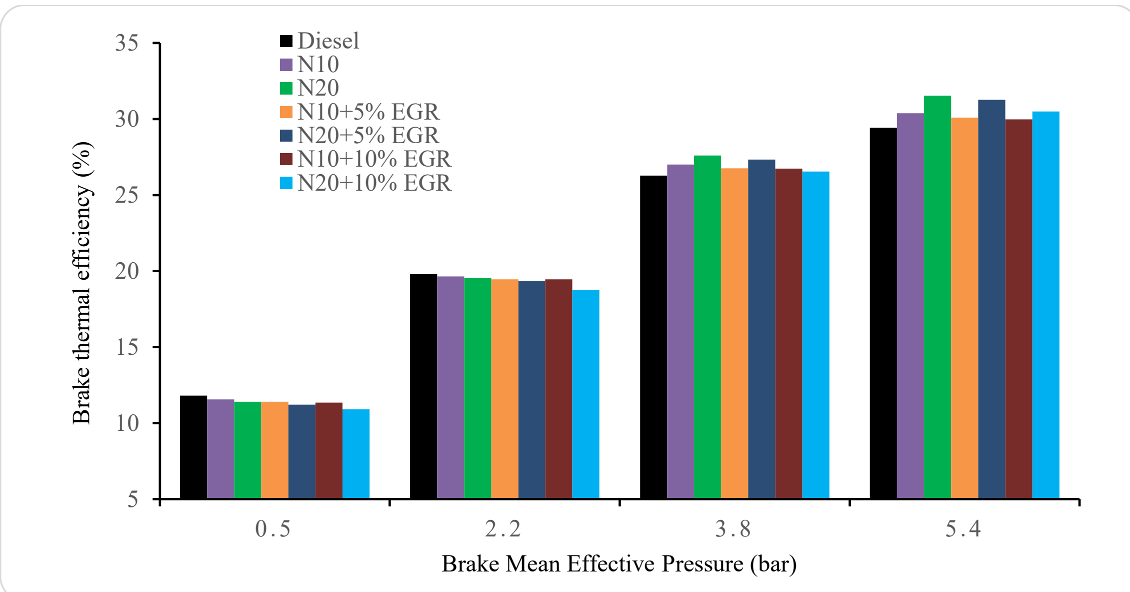



Fig. 4: Changes in BTE with BMEP.

Fig.5 depicts the relation between BSEC and BMEP for various test fuels and test conditions. From the figure that BSEC decreased with an increase in load for all test fuels. BSEC exactly followed the inverse trend as that of BTE for all conditions and test fuels.

For neat biodiesel blends N10 and N20, BSEC increased by 0.29% and 0.92% respectively as compared to diesel fuel at low loads whereas at high loading conditions BSEC for both fuel blends reduced by 9.0% and 11.4% respectively. The reason for these variations can be attributed to the same factors responsible for BTE variation. Meanwhile, EGR inclusion affects BSEC negatively at all loading conditions. A sharp increase in BSEC was observed for all test fuels with both 5% and 10% EGR addition.

At low load, introducing 5% EGR at intake increased the BSEC of N10 and N20 blends by 1.4% and 1.7% as compared to neat biodiesel blends without EGR. Meanwhile, the same trend was followed at high loading conditions where a hike of 1.5% and 2.4% BSEC was observed for N10 and N20 with 5% EGR. Further addition of EGR at 10% increased BSEC by 2.1 % and 3.8% at peak loading conditions for N10 and N20 blends respectively. The displacement of fresh oxygen in the combustion chamber by burnt gases causes a deficiency in oxygen level which reduces combustion temperature and efficiency. This, in turn, increases BSEC and reduces BTE for all test fuels in this present study.

**Emission Characteristics**

The variations in carbon monoxide emission with biodiesel operation with various EGR percentages are given in Fig. 6. Commonly, CO is a by-product of incomplete combustion that occurs during power stroke due to various phenomena. CO emission greatly depends upon the fuel-air ratio relative to the stoichiometric proportions and also depends upon the temperature prevailing inside the combustion chamber. Rich combustion zones consistently increase CO emission with deviation from stoichiometry (Salim Mohamed 2003, Raheman & Ghadge 2008).

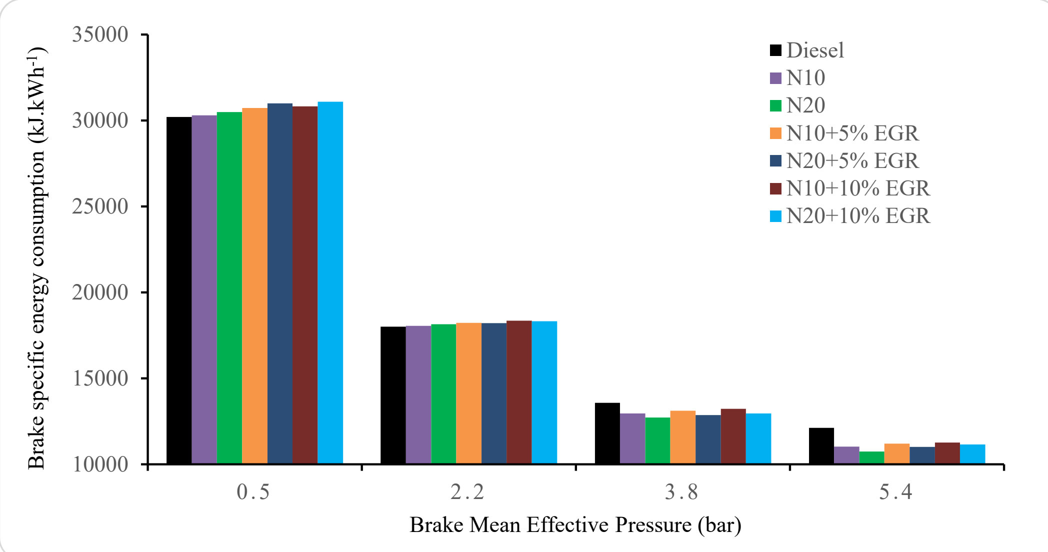



Fig. 5: Changes in BSEC with BMEP.

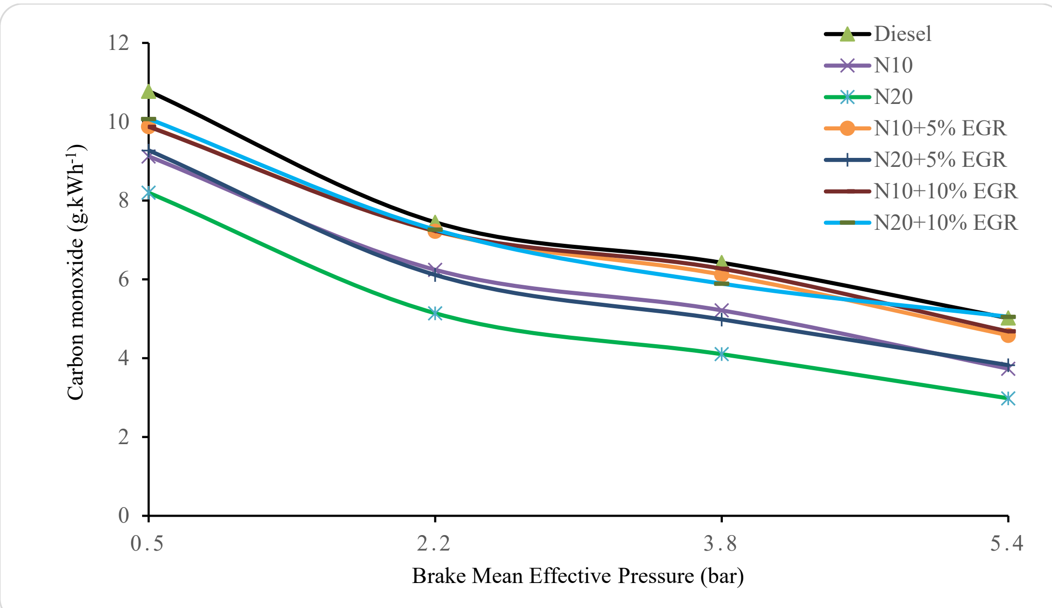



Fig.6: Changes in carbon monoxide with BMEP.

From the figure, it is evident that CO emission is decreased for all loading conditions while operated with Neem biodiesel blends. At low loads, N10 utilization reduced the CO emission by 15.4% and N20 by 23.9% as compared to baseline diesel fuel. Meanwhile, once the load is increased, CO emission drops for all test fuels and conditions. At maximum load, when compared to diesel operation, CO diminished by 25.7 % for N10 and 40.6% for the N20 blend. This reduction in CO is credited to high in-cylinder temperature produced by adequate fuel-air mixing and higher oxygen content of biodiesel fuels.

While incorporating EGR to the engine operation along with the neem biodiesel, CO emission is augmented with respect to biodiesel blend (N10 and N20) operation. With 5% EGR inclusion, CO emission of N10 and N20 blends increased by 18.6% and 28.2% at full load as compared to a straight biodiesel blend. Further increasing the EGR percentage to 10% for N10 and N20 blends, amplified the CO emission by 25.5% and 41.0% as compared to emission observed in respective biodiesel blends. This is due to incomplete combustion caused by the dilution effect of exhaust gases re-circulated.

Unburnt hydrocarbon emission is one of the most important parameters that quantify the completeness of combustion. In general CO and UHC, emission follows the nearly same trend for a particular mode of operation. Fig. 7 depicts the relationship between UHC and BMEP for all test conditions. UHC emission was reduced while running with biodiesel fuel under all loading conditions.

At full load operation biodiesel blends N10 and N20 reduced UHC emission by 14.2% and 31.2% with respect to neat diesel operation. This can be explained by the enhanced oxygenated nature of biodiesel fuels which increases combustion temperature and thereby reduces exhaust UHC emission. On the other hand, EGR introduction in the intake augments UHC emission at the exhaust.

When 5% EGR is tested with biodiesel blends at full load, it was observed that UHC emission increased by 5.8% and 11.3% for N10 and N20 blends as compared to straight NME biodiesel operation whereas further raising EGR to 10% amplified the UHC emission by 10.7% and 27.8% for aforesaid blends respectively. The hike in UHC could be made clear by dilution of intake charge with exhaust gas which shows the way to a reduction of oxygen required for complete combustion.

Fig.8 shows the trend of Carbon dioxide variations with respect to brake power for all testing modes. While augmentation of CO and UHC depicts incomplete combustion, $CO_2$ is the direct measure of the completeness of combustion. Even

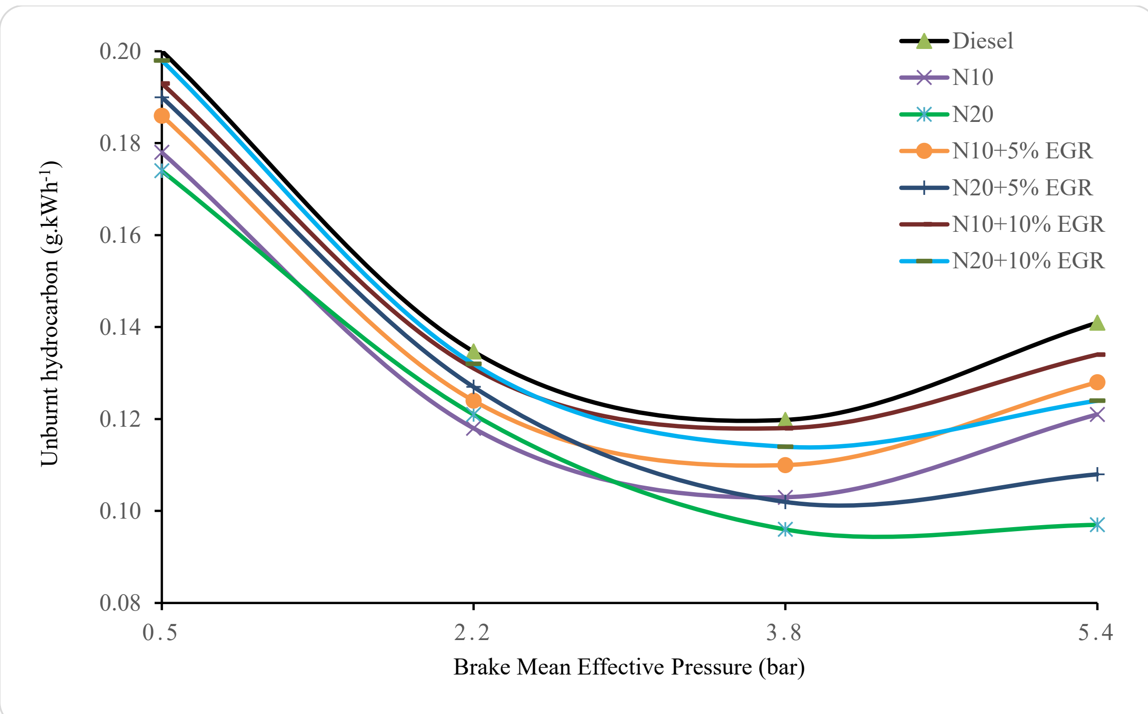



Fig. 7: Changes in unburnt Hydrocarbon with BMEP.

though the concentration of $CO_2$ in the atmosphere leads to global warming, the main of this testing is to enhance $CO_2$ emission since biodiesel utilization recycles carbon from feedstock to the atmosphere which constitutes a closed carbon cycle. Also, $CO_2$ emission follows a trade-off behavior with CO which is observed from the results.

At all loads, biodiesel operation increased the $CO_2$ emission to that of diesel operation. In specific, N10 and N20 blends amplified $CO_2$ emission by 9.4% and 42.7% at peak loads whereas 11.5% and 17.8% hikes were observed at lower loads. This is owing to complete combustion driven by more oxygen supply of NME biodiesel blends (Suja & Nagarajan 2018). On examining EGR effects on $CO_2$ at higher load, it could be deduced that $CO_2$ is reduced with increasing EGR percentage. With 5% EGR, $CO_2$ emission lessened by 9.3% and 14.7% for N10 and N20 blends as compared to neat biodiesel fuel blends. Meanwhile increasing EGR to 10% further reduced $CO_2$ by 15.3% and 22.5% for N10 and N20 under the same conditions. This inverse trending of $CO_2$ with respect to CO at EGR incorporation can be explained by instability in combustion and oxygen deficiency that makes $CO_2$ concentration decrease and CO increase (Mani et al. 2010).

Oxides of nitrogen are normally formed when oxygen and nitrogen react at high temperatures during the combustion process. Indirect injection of fuel, fuel is atomized into finer droplets where oxygen reacts at the boundary of fuel-air. Due to the burning of fuel, the localized temperature in the vicinity of droplets exceeds the limit at which NOx is formed. Since diesel engines always run in high compression ratio and lean air-fuel mixture, high cylinder temperature prevails during combustion which is the most favorable condition for NOx formation. The NOx emissions are evaluated by the oxygen concentration in the cylinder, equivalence ratio, temperature, and time. NOx during engine operation is predominately formed due to uncontrolled combustion which creates localized high-temperature zones. Fig. 9 illustrates the relationship between NOx and BMEP for different EGR percentages.

From the figure, the NOx emission increased for biodiesel at all loading conditions. In comparison with neat diesel operation, the biodiesel blends N10 and N20 showed 22.8% and 23.7% high NOx at lower loads whereas at high loads the same biodiesel blends showed 22.3% and 52.8% hike in NOx rating. Even though NOx is inevitable in biodiesel operations, it can be reduced by the techniques like EGR, exhaust gas treatment, and fuel additives. Among these NOx reduction techniques, EGR is a reliable technique that can diminish NOx magnitude at the exhaust. The results of this

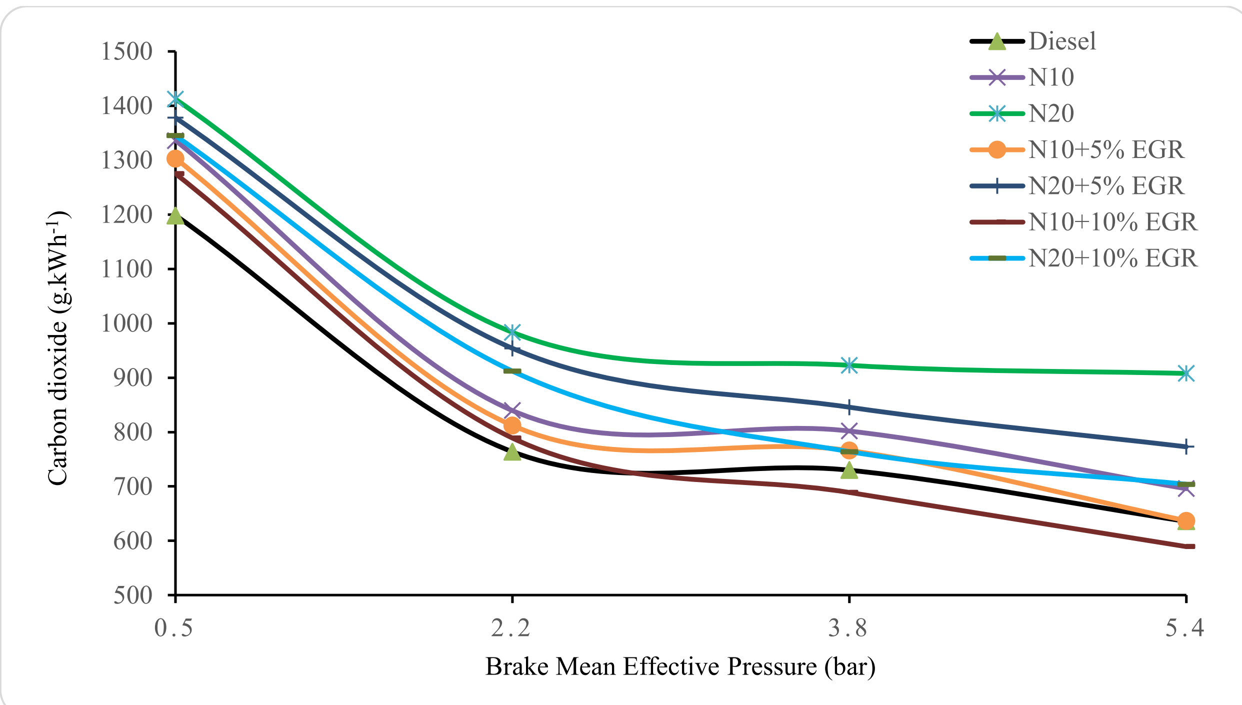



Fig 8: Changes in carbon dioxide with BMEP.

experimental study clearly show that the incorporation of EGR reduces NOx emission at the exhaust. For the N10 blend, EGR at 5% and 10% reduced NOx emission by 38.6% and 44.5% at peak load. Meanwhile, for the N20 blend, incorporation of EGR at 5% and 10% diminished NOx values by 32.3% and 37.8% at peak load than neat biodiesel. The increase in NOx values in biodiesel operation is attributed to the increased oxygen content of the fuel that enhances combustion which in turn elevates peak cylinder temperature. Higher in-cylinder temperature leads to a hike in NOx emission (Bhupendra et al. 2013). On the other hand, as EGR is introduced with a fresh charge increases the specific heat of the charge, thus decreasing the temperature rise inside the cylinder which in turn reduces NOx elevation (Mani et al. 2010, Nitin et al. 2016).

The changes in smoke emission with BMEP are revealed in Fig. 10. Lesser smoke emission is evidenced when the diesel fuel is enriched with NME biodiesel. The smoke emission in neat diesel operation is higher due to the presence of aromatic hydrocarbon structure which enables thermal stability and a higher boiling point.

NME biodiesel has zero aromatic compounds and more oxygen contents which helps with smoke formation (Suja & Nagarajan 2018). Smoke emission is observed in neat diesel operation from 16 to 54% from 0.5 to 5.4 bar BMEP and the same is noticed from 11.5 to 44% for N10 and from 9 to 38% for N20 operation. Combustion is enhanced at fuel-rich zones in NME biodiesel operation due to the presence of fuel-borne oxygen with respect to neat diesel operation where no fuel-borne oxygen. The introduction of EGR impacted the increase in smoke emission owed to incomplete combustion caused by reducing the oxygen availability for combustion. The increases are observed in higher loads as 12.7 and 15.5% for 5% EGR, like 18.4 and 20.8% for 10% EGR for N10 and N20 respectively when compared to biodiesel operation.

## Combustion Characteristics

Combustion characteristics of Neem oil biodiesel and EGR effects on it were analyzed by measuring the cylinder pressure against crank angle degrees (CAD). The pressure data was measured for 100 consecutive cycles and values were averaged and then used to calculate heat release rate and cylinder pressure to avoid variations. From the obtained pressure data, the heat release rate can be derived by the first law of thermodynamics equation given below,

$$\frac{dQ(\Theta)}{d\Theta} = \frac{1}{\gamma - 1}[V(\Theta)\frac{dP(\Theta)}{d\Theta} + \gamma P(\Theta)\frac{dV(\Theta)}{d\Theta}]$$

Fig. 11 depicts the in-cylinder pressure variations with CAD at full loading conditions for all test conditions. It is seen that the maximum cylinder pressure decreased with an

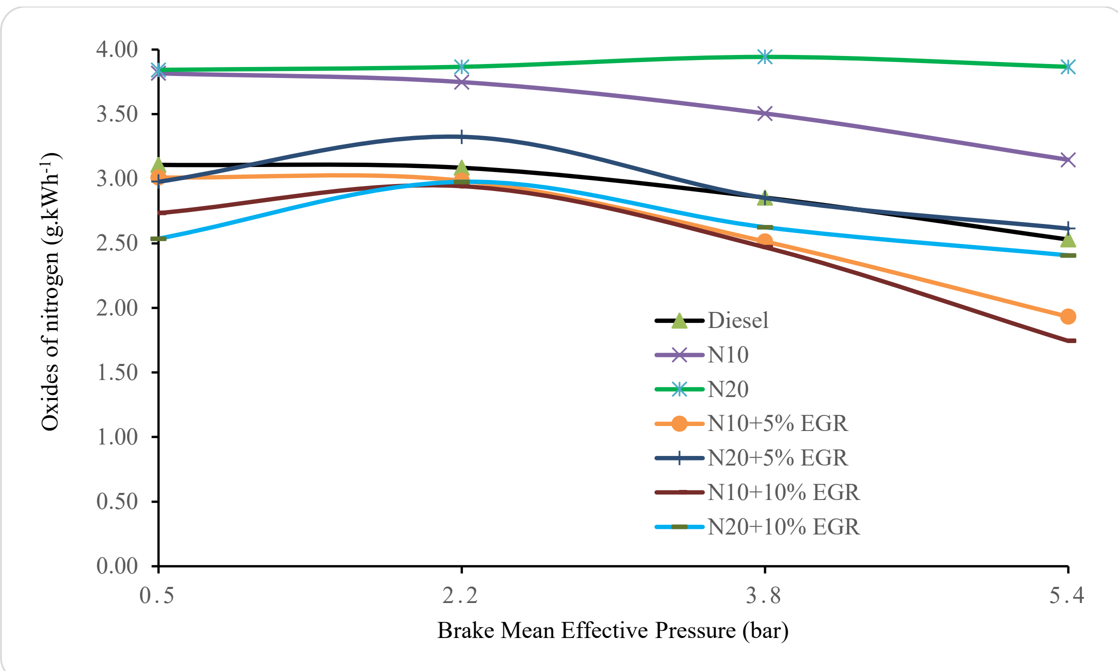



Fig. 9: Changes in oxides of nitrogen with BMEP.

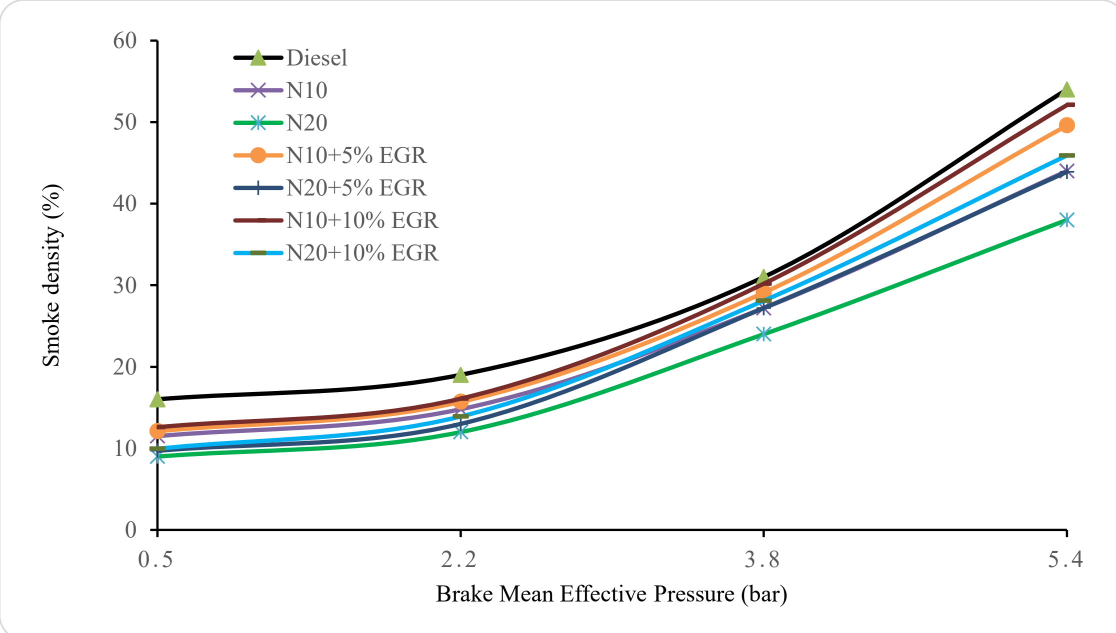



Fig.10: Changes in smoke density with BMEP.

increase in biodiesel concentration in the test fuels for all EGR conditions.

Neat diesel fuel displayed an extreme cylinder pressure of 50.4 bar at 15° after top dead center (ATDC), N10 and N20 blend showed maximum peak cylinder pressure of 48.1 bar and 47.6 bar at CAD of 10° and 7° ATDC respectively. In general biodiesel fuel properties like high viscosity, low volatility and high cetane number are major aspects that affect the variations in peak cylinder pressure (Rashedul et al. 2015).

It is worth noting that the start of combustion (SOC) is advanced with biodiesel addition as referred to as baseline diesel fuel. It is due to advancements in dynamic injection timing in lieu of higher bulk modulus of biodiesel fuel (Lahane & Subramaniam 2014, Subramanian & Lahane 2013, Yu 2007). Another possible reason for this advancement in SOC may be the higher cetane number of biodiesel. As EGR was introduced into operation, significant variations in cylinder pressure were observed. The SOC was retarded for all biodiesel blends with the addition of EGR, which may be attributed to an increase in the specific heat capacity of EGR and reduction in the availability of $O_2$, which further contributes to weakens combustion rate resulting in peak cylinder pressure decrement (Nitin et al. 2016). Besides, dissociation of $H_2O$ and $CO_2$ contributes to the flame temperature reduction resulting in NOx reduction because of the endothermic process (Domenico et al. 2017). It can be noted that 5% EGR addition resulted in a decrease in peak pressure to 47.4 bar and 46.9 bar for N10 and N20 blend respectively. Meanwhile further increase in EGR rate to 10% for N10 and N20 blends decreased the peak cylinder pressure to 46.7 bar and 45.8 bar respectively.

Fig. 12 depicts the variations in HRR with CAD at peak load for the test fuels employed in this study. From the figure, it is evident that the incorporation of EGR greatly influenced in $HRR_{max}$ variations.

Many literature studies revealed that the biodiesel addition to the neat diesel may cause a minor drop in the $HRR_{max}$ value due to shorter premixed combustion duration, lower heating value, early SOC timing, and poor spray characteristics of the biodiesel fuel (Ozener et al. 2014, Ozturk 2015). A similar trend was observed in this study where $HRR_{max}$ recorded for diesel fuel was 55.1 $J.CA^{o-1}$ and the subsequent addition of biodiesel fuel with EGR decreased the $HRR_{max}$ values. NME biodiesel blends N10 and N20 showed a maximum HRR of 54.5 $J.CA^{o-1}$ and 54.1 $J.CA^{o-1}$ respectively. In addition to this, the location of $HRR_{max}$ was noted to shift towards TDC with biodiesel addition to all engine loads. On the other hand, incorporation of EGR along with biodiesel fuel leads to a further decrease in $HRR_{max}$ as compared to that of biodiesel blend operation. Biodiesel blend N10 along with EGR of 5% and 10% decreased $HRR_{max}$ by 1.7 % and 2.9 % respectively whereas N20 blend along with EGR of 5% and 10% decreased the $HRR_{max}$ by 1% and 3.3%

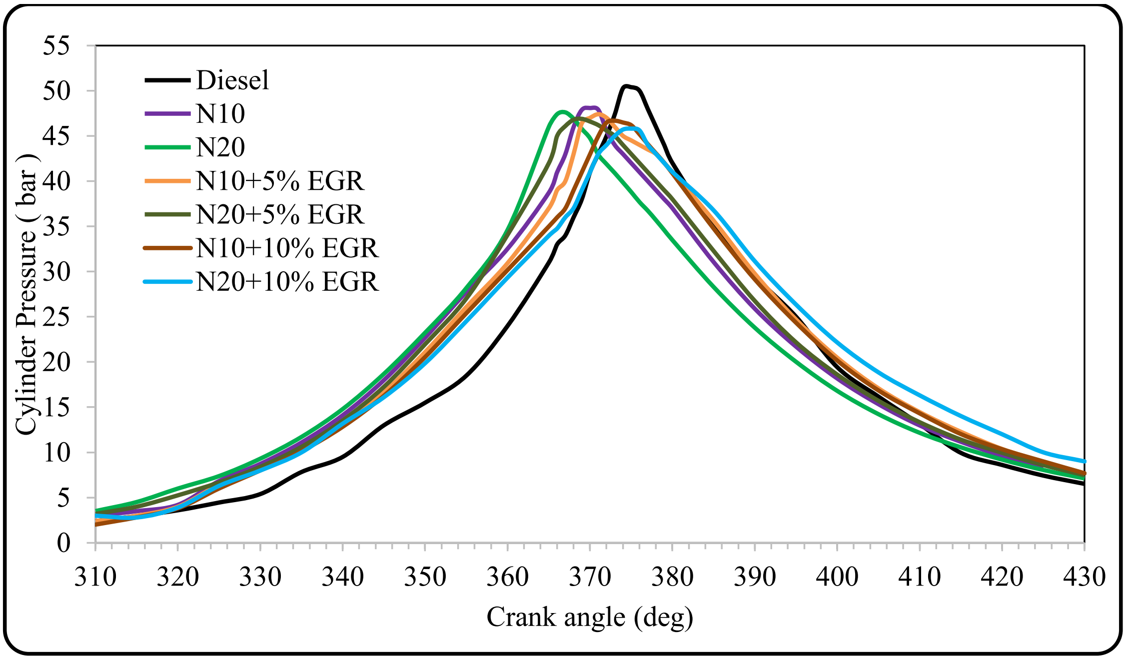



Fig.11: Changes in cylinder pressure with CAD.

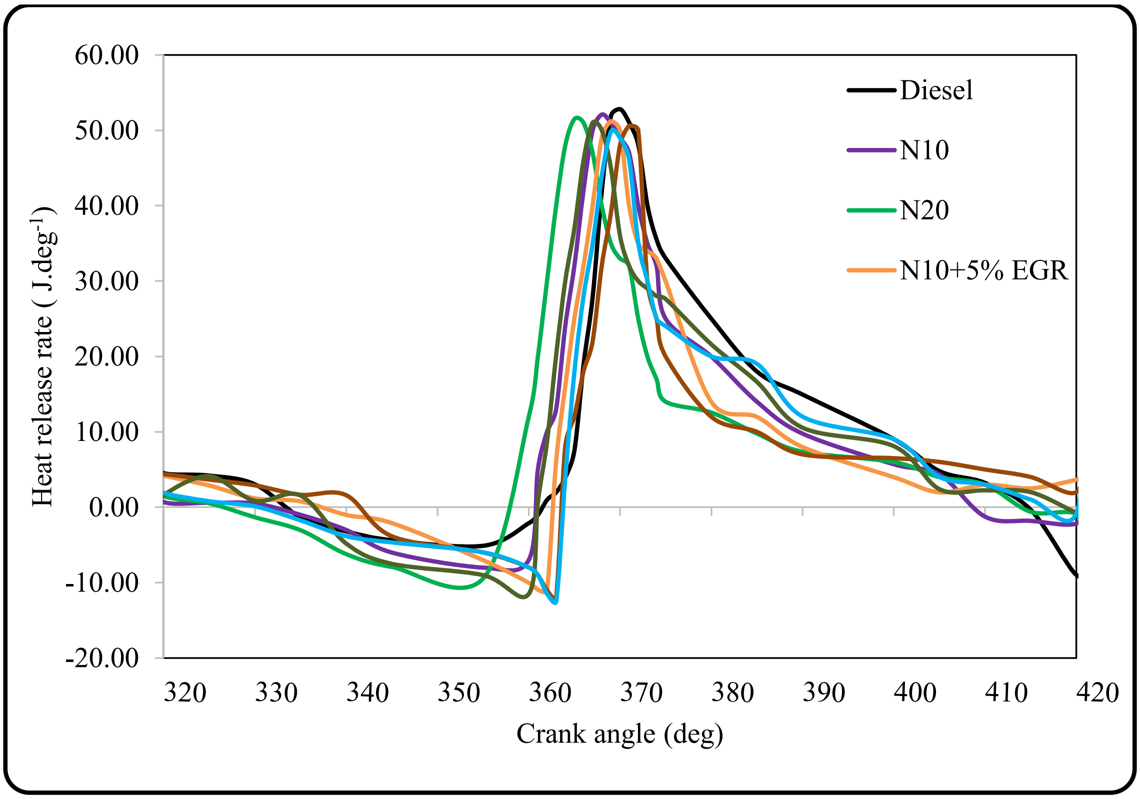



Fig. 12: Changes in HRR with CAD.

respectively as compared to corresponding biodiesel blend operation.

### Trade-off Study

Trade-off studies between BSEC and NOx, Smoke, and NOx were carried out to understand the optimum proportion of NME biodiesel and EGR rate at a maximum BMEP of 5.4 bar, and the same is depicted in Fig. 13 and Fig. 14. It is noted that the blending of Neem oil methyl Ester of 10 and 20% with diesel fuel improves the BSEC and smoke emission by decreasing BSEC by 9 and 11.4% and smoke density by 18.5 and 29.6%, however, the NOx emission level increased by 24.4 and 52.8% respectively for N10 and N20 than neat diesel operation. The adverse impact of NOx emission increase was controlled by introducing EGR with marginal compromise on performance (BSEC) and smoke density, however better than diesel operation.

From the trade of study, optimum biodiesel and EGR combination were understood at N20+5% EGR where BSEC and smoke density reduced by 9.2 % and 18.7 % respectively with that of neat diesel operation and the NOx emission is at par with diesel operation.

## CONCLUSION

In this present investigation, the effects of the combination of 10% and 20% Neem oil Methyl Ester biodiesel and various EGR rates of 5% and 10% on the characteristics of a DI diesel engine were studied experimentally. The outcomes are as follows:

- The NME biodiesel blends improved the performance characteristics by increasing the BTE by 3.3 and 7.2 % and reducing the BSEC by 9 and 11.4% for 10 and 20% biodiesel blends respectively at peak loads compared to neat diesel. The hike in BTE can be explained by the presence of oxygen in fuel which enhances combustion efficiency. On the other hand, the incorporation of EGR along with biodiesel reduced BTE and increased the BSEC of the engine under all loading conditions. The displacement of fresh oxygen in the combustion chamber by burnt gases causes a deficiency in oxygen level which reduces combustion temperature and efficiency.
- Improvements in unburnt hydrocarbon and carbon monoxide emissions were obtained by the use of a biodiesel fuel blend at all loading conditions, while deterioration

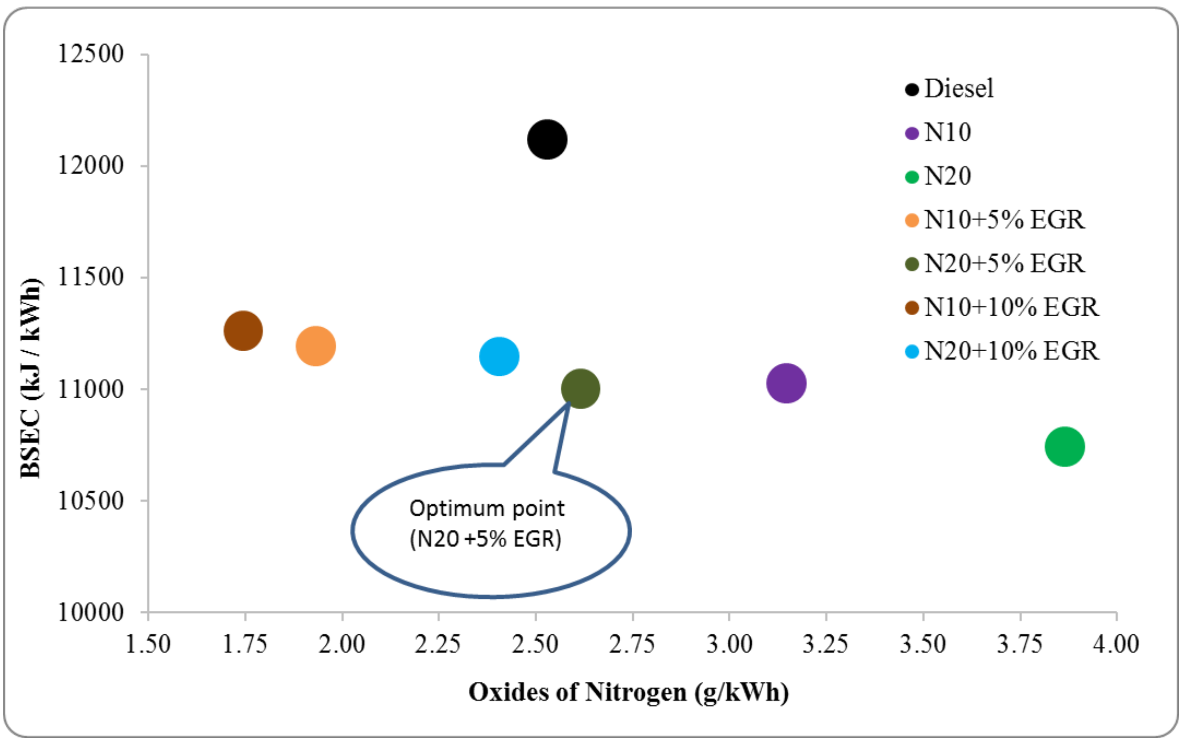



Fig. 13: Trade-off study between BSEC and NOx.

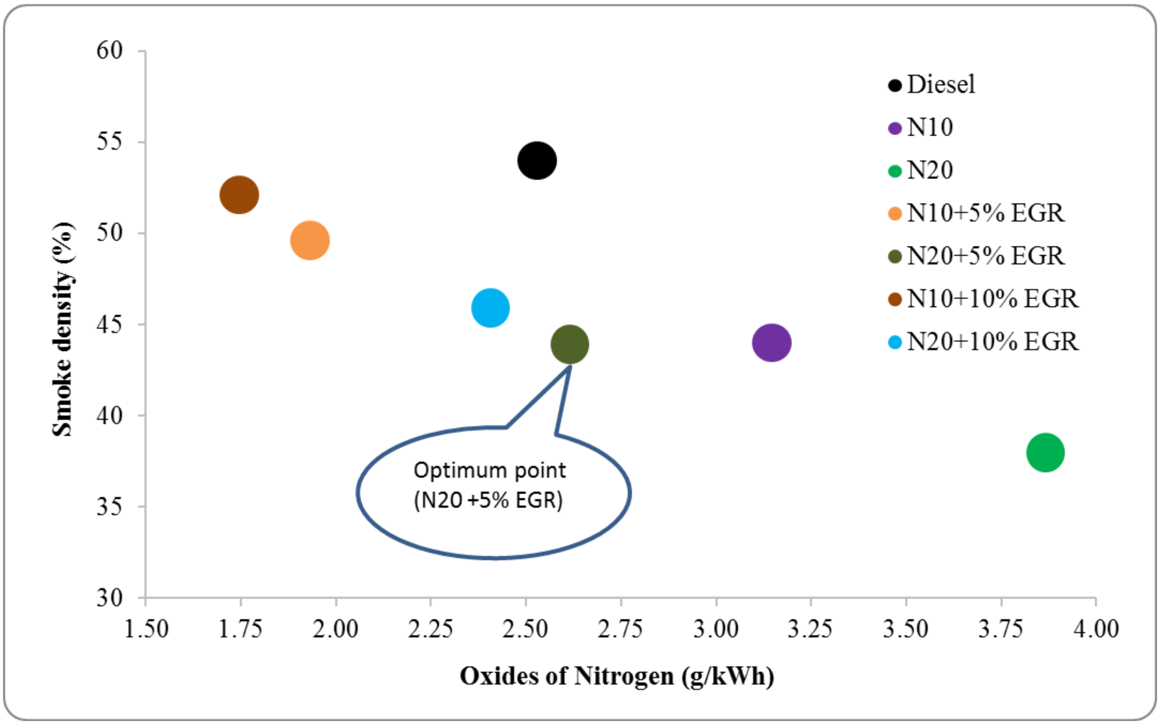



Fig. 14: Trade-off study between Smoke density and NOx.

occurred when EGR was added to the operation. UHC emission was decreased by 14.2 and 31.2%, CO emission was decreased by 25.7 and 40.6% for N10 and N20 respectively at maximum load with respect to neat diesel operation. This reduction in UHC and CO can be attributed to high in-cylinder temperature caused by adequate fuel-air mixing and oxygen content of biodiesel fuels. The rise in CO and UHC can be explained by dilution of intake charge with exhaust gas which leads to a reduction of oxygen needed for complete combustion. This increase is only with respect to biodiesel operation with no EGR condition, however lower than neat diesel operation.

- Augmentation in $CO_2$ levels up to 42.7 % during N20 biodiesel operation showed the degree of completeness of combustion whereas the addition of EGR at all rates deteriorated $CO_2$ levels in the exhaust up to 22.5% for N20 with 10% EGR due to dilution effects of the intake charge.
- The higher penalty in NOx was observed during biodiesel utilization which is most commonly due to the high in-cylinder temperature that prevailed in biodiesel operation. The combination of biodiesel and EGR reduced harmful NOx emission at exhaust by reducing in-cylinder temperature through the thermal and dilution effects of the intake charge. The increase in NOx was observed as 22.3 and 52.8% for N10 and N20 respectively at maximum load with respect to neat diesel operation. In the biodiesel operation of N10 with 10% EGR, the NOx level was reduced by 44.5 % with respect to N10 with no EGR and by 31 % with respect to neat diesel operation. At N20 with 10% EGR, the NOx level was reduced by 37.8% compared to N20 with no EGR and by 4.9 % compared to neat diesel operation.
- Smoke emission is observed in neat diesel operation from 16 to 54% from 0.5 to 5.4 bar BMEP and the same is noticed from 11.5 to 44% for N10 and from 9 to 38% for N20 operation. Combustion is enhanced at fuel-rich zones in NME biodiesel operation due to the presence of fuel-borne oxygen with respect to neat diesel operation where no fuel-borne oxygen. The introduction of EGR marginally impacted the raise in smoke emission with respect to neat NME biodiesel operation due to incomplete combustion caused by reducing the oxygen availability for combustion, but lower than the neat diesel operation for all EGR combinations.

On the whole use of Neem oil Methyl Ester of 10 and 20% along with EGR of 5 and 10% put a step towards reducing harmful NOx emission which is the major setback in using biodiesel as a commercial fuel. Also, improvements in performance characteristics further confirm the potential of Neem biodiesel (20% ) along with the 5% EGR can be used in commercial transportation.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| BMEP | Brake Mean Effective Pressure | EGR | Exhaust Gas Recirculation |
| BSEC | Brake Specific Energy Consumption | HCCI | Homogeneous Charge |
| BSFC | Brake Specific Fuel Consumption | | Compression ignition |
| BTE | Brake Thermal Efficiency | ID | Ignition Delay |
| CAD | Crank Angle Degree | NME | Neem oil Methyl Easter |
| CI | Compression-Ignition | NOx | Oxides of Nitrogen |
| CO | Carbon monoxide | SOC | Start of Combustion |
| CO2 | Carbon dioxide | SOI | Start of Injection |
| DI | Direct Injection | UHC | Unburnt Hydrocarbon |

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