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Original Article

Experimental Analysis and Investigation on Enhanced Combustion and Reduced Emissions of Diesel Engines Using Emulsified Biodiesel

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Abstract *- This study investigated the combustion characteristics of an engine fueled by BD25% (Pongamia biodiesel) blended with water (5, 10%, and 15%) and 1% Span80 emulsions. The findings were compared to those obtained from biodiesel fuel. The primary goal of this study is to employ water addition as a means to alleviate the detrimental effects caused by a significant decrease in NOx and smoke emissions compared to HC and CO. To achieve a highly uniform emulsified fuel mixture, the following compositions are used: Diesel, 25% BD, Water, and Surfactant Span 80. The proportions of these components are as follows: D69:B25: W5:S1 (EBD1), D64:B25: W10:S1 (EBD2), and D59:B25: W15:S1 (EBD3). These solutions are mechanically agitated for approximately 45 minutes. By retaining the mixture in a beaker for 48 hours, the stability of the emulsified fuels EBD1, EBD22, and EBD3 was examined, and it was found that there was no dissolution of the water from the fuel. Experiments have been carried out on a diesel engine under various loads using diesel, BD25, EBD1, EBD2, and EBD3 fuels. The outcomes showed that in comparison to the 25% biodiesel blend, NOx emissions from the engine using EBD3 emulsified fuels were drastically reduced by 47.25%. In comparison to the BD25 blend, the EBD3 emulsified fuel had CO and HC emissions that were increased by 28.6%, and 32%, respectively. A higher water concentration lowers NOx emissions, and the emulsified fuel performs better than other test fuels in terms of HC, and CO emissions at peak power conditions.*

Keywords *- Emulsion, Biodiesel, Emission, Combustion, Diesel engine, Performance.*

1. Introduction

Recently, diesel engines have been dominant in the heavy-duty manufacturing and mobility sectors since they consume more fuel and have higher engine efficiency compared to petrol engines. [1]. Nevertheless, the significant amounts of NOx, PM, and sulfur oxides from the engine are harmful to the ecosystem and result in acid rain and warming the planet. Rigorous emission laws are mandated globally to cut down on emissions of fossil fuels in demand to mitigate the opposing belongings of emissions. Additionally, globalization and growth in industrialization are to blame for the century's ongoing rise in worldwide fuel use [2].

As a result, numerous investigators and creators have been working to enhance engine new methods in order to fulfil the standards [3]. In diesel engines, biodiesel is one of the replacements that may mitigate emissions such as carbon monoxide and unburned hydrocarbons. However, this fuel has the potential to increase NOx pollution emissions, which are harmful to both humans and the atmosphere [4]. Due to their lower exhaust emissions, biofuels like biodiesel are the most viable fuels for diesel engines due to their reduced exhaust emissions, unburned hydrocarbon particulate matter, poly-aromatics, renewability and biodegradability [5].

So, utilizing the transesterification process, vegetable oils can be transformed into biodiesel. Biodiesel is a viable alternative fuel that offers broadly satisfactory performance, reduces emissions, and does not call for any engine adjustments [6]. Either delaying injection timing or adding the (EGR) system can lower emissions like NOx. However, this is also accompanied by a rise in smoke and the use of particular fuels.

Through the use of preprocessing and post-processing emission control strategies, a number of researchers have attempted to lessen the NOx in diesel engines. Out of these, the preliminary emission reduction approach used in the current study is the inclusion of water as the base fuel because the base fuel that has been emulsified improves engine performance and fuel efficiency while also reducing adverse emissions [7].

Emulsified fuels simultaneously reduce the NOx and smoke as it suppresses the combustion chamber temperature [8]. Diesel fuel that has been water-emulsified increases BTE and reduces BSFC while increasing macro-explosion magnitude, air which enters, and the premixing ignition [9]. The substantial thermal heat absorption of water contents during ignition could decrease the local flame temperature, thereby decreasing NOx emissions.

Mondal and Mandal generated a water-emulsified diesel fuel and observed a rise in BTE while reducing the amount of BSFC by incorporating 10% water into diesel; despite a reduction in CO emissions, NOx and smoke emissions were significantly reduced. Utilizing fuel that has been water-emulsified can considerably cut emissions without significantly affecting the amount of gasoline used.

According to [10], adding water increases the fluid viscosity of diesel fuel while lowering its heating value and cetane number. High fuel density gives fuel more momentum, which enhances the fuel mixing air method and principles to better fuel combustion. The NOx emissions, carbon dioxide (CO_2) emissions, and hydrocarbon emissions can all be decreased by using diesel-biodiesel-water mixes, a type of water-in-oil emulsion fuel [11].

Since water has a lower boiling point than oil, it is added to diesel and biodiesel fuel blends as an interior phase emulsion; during combustion within the cylinder, the water the droplet initially evaporates and then detonates into small particles of fuel, bringing about micro-explosion, which minimizes the combustion chamber's temperature and improves combustion efficiency [12, 13].

[14] investigated the effects of 20% of BD and its water emulsion on engine performance value. Results showed that employing B20E5 produced a torque improvement of 28.4% and a decrease in BSFC. Peak pressure decreases substantially when using B20E5. Compared to diesel fuel, the combined fuel B20's 30% water component decreased NOx emissions, as noted as 26.17%.

The effectiveness of diesel-water nanoemulsion with various surfactant levels on diesel engines has been studied by [15]. Test results showed that improved BP and BTE were obtained and maximum reduction in NOx emissions with 0.40% surfactant and 0.90% water solutions. The outcome of using fuel diesel emulsion on engine performance behaviours was assessed by [16]. The findings showed that 2% W/D fuel had the lowest BSFC, and significantly lower combustion temperatures for W/D fuel at 5, 8, and 10% resulted in higher CO and lower CO_2 emissions. Compared to diesel, emulsified fuel lowered engine NOx by lowering the combustion temperature. [17] suggested that introducing small amounts of water to B5 could dramatically reduce other emissions. The ideal water added to the in terms of the level of engine performance characteristics has been found to be 4 wt%.

[18] examined how efficiency and emission measurement parameters were affected by a nanoemulsion fuel consisting of 5% water, 5% biodiesel, and 5% surfactant. The findings demonstrated a considerable reduction in the generation of smoke opacity when nanoemulsion fuel was used. On the other hand, CO_2 emissions increased somewhat.

[19] investigated how adding liquid up to 32% with 3% polysorbate surfactant affected the diesel engine's emissions and performance. Even though there was a maximum NOx decrease of 68.14% with a 32% liquid addition compared to diesel, they found that the BTE increased by 3.34% when associated with diesel with an 8% water addition. The ratio of diesel, water, ethanol, and biodiesel in emulsions for a diesel engine was researched by [20].

They claimed that a biodiesel-water emulsion increased the BTE to 7% at full power as opposed to 3% with an ethanol emulsion. The biodiesel-water emulsion performed better, with maximum reductions in NOx and smoke emissions of 45%, and 37%, respectively. The biodiesel-water emulsion knowingly decreased (CO) emissions by 54% at supreme power.

1.1. Research Gap

Several studies have been described in the literature that utilise micro emulsion derived from vegetable oils to analyse the engine characteristics and properties of diesel engines. The main goal of this research is to evaluate the potential of utilising micro-emulsion derived from Pongamia BD as a fuel for investigating engine characteristics, including performance, emissions, and combustion evaluation. The aim is to concurrently diminish nitrogen oxide and smoke emissions in a single cylinder, unmodified stationary diesel engine.

2. Materials and Methods

2.1. Preparation of Biodiesel

The unrefined pogonamia oil was purchased from the Chennai market. The water droplets present in the pongamia oil were eliminated using a process of filtration, followed by boiling the oil to a temperature exceeding 100°C and subsequently cooling it to room temperature in a refrigerator. 30% methanol by capacity and 1% KOH by weight were combined to create the methoxide solution. The generated methoxide solution is now combined with the raw oil in a beaker and stirred for one hour at 65°C reaction temperature. A magnetic stirrer stirred the mixture and then provided it with 24 hours to settle. Two layers were formed in the beaker.

The highest layer was biodiesel, and glycerin was in the lowest layer. The ester's top layer was split apart. The remaining glycerin and catalyst from the separated ester have been eliminated by washing it with warm water that had been distilled before heating it to 110°C to evaporate the moisture.

2.2. Emulsified Fuel Blend Preparation

The biodiesel-diesel blend is designated BD25 and combined with diesel in a volume ratio of 25:75. The fuel's ability to maintain a stable emulsion for an extended period of time can be improved by choosing the suitable surfactant and emulsification technique.

In comparison to cationic and anionic surfactants, nonionic surfactants improve in the aspects mentioned above. According to the emulsification method, the ultrasonic and supersonic processes are typically used for surface tension cropped moving and homogenizing under high pressure. The biodiesel-diesel was mixed and emulsified by adding water at levels of 5%, 10%, and 15%, along with surfactants at 1%. For a highly uniform mixture, Span80 surfactant was added in the capacity of tiny dewdrops and agitated with a high-velocity agitator for around 45 minutes. This mixture is designated as EBD1, EBD2 and EBD3, respectively, for 5%, 10% and 15% water. By storing all of the mixture in a cup for 72 hours, it was physically tested to ensure that there was no fuel or water parting. The ASTM-tested and listed attributes of the prepared combinations are in Table 1. Figure 1 contains a flowchart that explains how biodiesel and various blends are prepared.

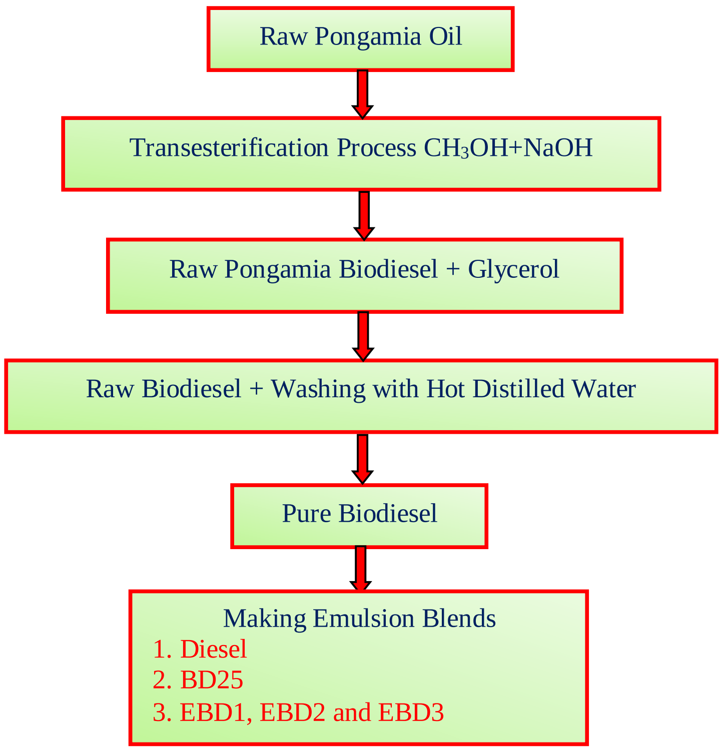

Fig. 1 Step-by-step process of biodiesel and emulsified biodiesel blends

Table 1. Properties of diesel & BD

Properties	Diesel	BD
Density (kg/m^3)	840	880
Kinematic Viscosity (cSt)	3.2	10.56
Flash Point (^{o}C)	52	176
Cetane Number	45	52
Calorific Value (kJ/kg)	42500	36000

2.3. Engine Set Up

A test engine was applied for the experiments, and the practical conditions of the engine are shown in Table 2. Figure 2 depict the experimental setup. A current ergometer that is associated with the engine loaded it. The different sensors and instrumentation combined with computerized data acquisition systems are used to quantity the functional load, air and fuel movement value, EG temperature, instantaneous CP, injection pressure, and crank angle position online.

The experiment was loaded with a maximum of 4.4 kW for this study with a step of 1.1, 2.2, 3.3, and 4.4 kW. Diesel and biodiesel fuel were stored in separate overhead fuel containers. The fuel for diesel and biodiesel was kept in separate overhead fuel tanks.

A conventional burette and a stopwatch are used to time how long it takes the engine to burn through 10 cc of fuel. An AVL 444 analyzer was used to measure the engine's exhaust emissions, such as HC, CO, and NOx, along with an AVL 437C. A smoke meter was utilized to measure the amount of exhaust gas and the opacity of smoke.

An encoder with a pressure transducer was used for measuring in-cylinder pressure and recording instantaneous crank angles, respectively. A static injection pressure and injection timing of 200 bar and 23°bTDC were set for the entire experimental work. With the support of a high-velocity automated data attainment system, the signals from various sensors have been acquired.

The signals that were collected for over 100 consecutive cycles were analyzed to produce the combustion parameters. Every five minutes, measurements of engine output and emissions for each fuel were conducted for each load to ensure that the results did not change. Each experiment set's three runs' means were recorded. The requirements for performance and soot emission were noted for each load condition.

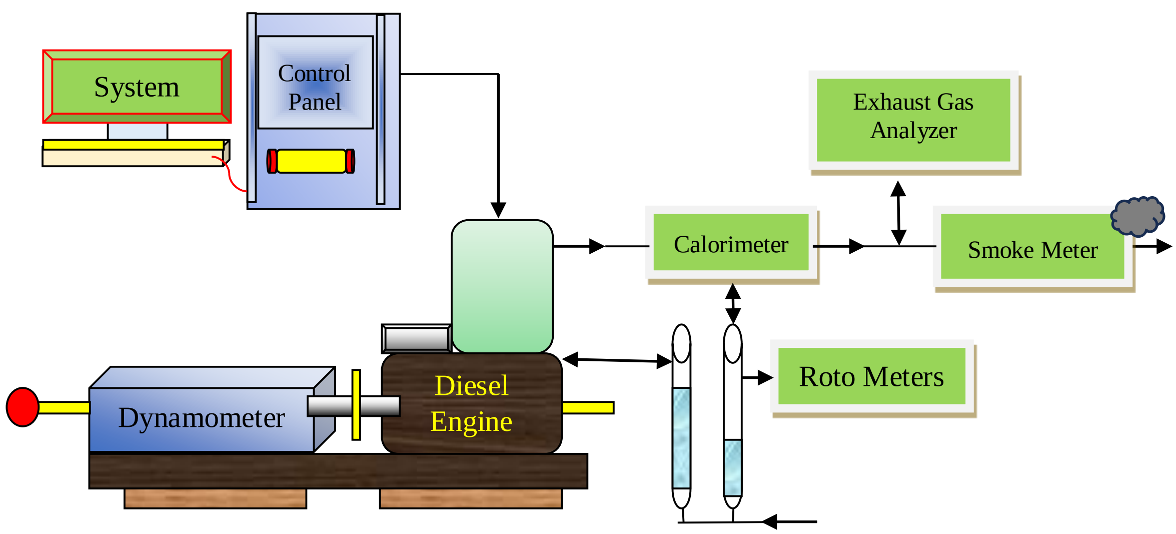

Fig. 2 Line diagram of the test engine

Table 2. Test engine technical details

Make	**Kirloskar, Vertical, 4S**
Borex Stroke (mm)	87.5 x110
Power (kW)	4.4
Comp. Ratio	17.5:1
Speed (rpm)	1500
Inject. Timing (°C)	23°bTDC
Inject. Pressure (bar)	200

2.4. Uncertainty Analysis

This study of uncertainty has separated errors into two small groups: random and fixed. Many things, like visualization, selections, etc., were used to predict the uncertainty and error analysis, which was then followed by time length. In order to get accurate data, uncertainty analysis is done. The method of root mean square, often known as the propagation of uncertainty methodology, was employed to compute the uncertainties.

2.4.1. Uncertainty

$$\varphi_R = \left[\left(\frac{\partial R}{\partial x_1}\varphi_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\varphi_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\varphi_n\right)^2\right]^{\frac{1}{2}} \quad (1)$$

A function called R depends on self-determining variables like multiple of 1, 2 & 3 and so forth. The uncertainty of the independent variables is well-defined as 1, 2, n, whereas R is well-defined as the overall proportion of investigational values' uncertainty in the results (Holman 2012). In instruction to confirm the accuracy of the test findings, an error investigation built on Taylor's theorem was employed. Uncertainty generally can be expressed by overall uncertainty.

3. Results and Discussion

Reviewing the performance characteristics is essential when considering alternative fuel modifications. The improved emissions, as well as the efficiency of an engine from modified fuel, make it economically viable to switch from the current diesel fuel. In an engine with a static compression value of 17.5 and a (VCR), the diesel and prepared blends have been evaluated. At various load circumstances, the engine's working behaviours were tested for each test fuel. The outcomes are demonstrated in this section.

3.1. Change of Cylinder Pressure with Crank Angle

Figure 3 demonstrates the change of averaged in-CP with crank angle for BD25, EBD5, EBD10, EBD15, and diesel at peak load. A peak in-cylinder compression of 64.91 bar was reported for diesel, 64.1 bar for EBD5, 63.79 bar for EBD10, and 63.16 bar for EBD15. The difference in peak pressures with emulsified blends was observed as compared with diesel.

From the literature, it was found that the cetane number of micro-emulsions is lower than diesel [12]; hence, the ignition delay is longer due to a higher premixed burning rate. Hence, the peak pressures of blends are reduced compared to pure diesel. In addition, dynamic injection timing was advanced for emulsion blends due to higher density. The in-cylinder pressure influences the fuel's capability to mix well and combust [14]. The difference in the in-cylinder pressures of blended fuels and diesel is marginal, which indicates its capability as fuel.

3.2. HRR

Figure 4 represents the change in HRR with CA for BD25, EBD1, EBD2, EBD3 and diesel at maximum load. The negative HRR observed for all fuels before combustion could be the evaporation of accumulated fuel in the ID period, whereas the HRR becomes positive after the initiation of combustion. During the vaporization of fuel injected privately, the combustion value absorbs heat from the combustion chamber, which causes a chilling effect with a negative value of HRR. The advance in dynamic injection timing allows for the injection of fuel in advance due to the greater density of emulsified fuel blends; however, it also prolongs the ignition delay by allowing for the growth of more fuel inside the combustion chamber [14].

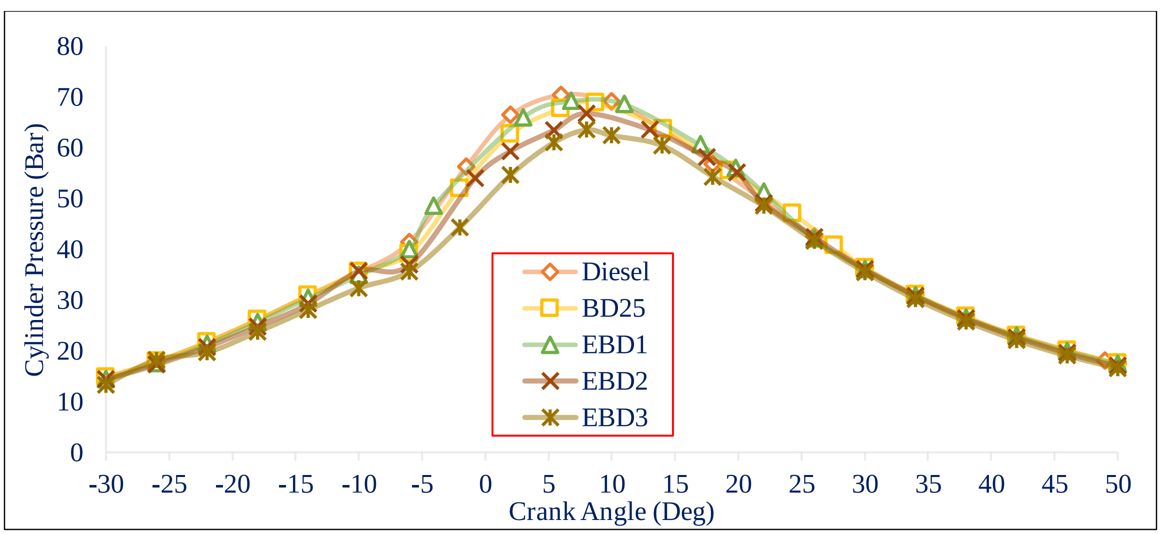

Fig. 3 Cylinder pressure vs CA

Diesel had a higher HRR of 66 J/°CA compared to 63 J/°CA with BD25, 59 J/°CA for EBD1, 57 J/°CA with EBD2 and 55 J/°CA with EBD3. The decrease in HRR was brought on by two factors: the micro-emulsion mixes reduced calorific value and their greater kinematic viscosity. Lower fuel/air mixing during the injection process, as a result of the higher kinematic viscosity, results in lower HRR for micro-emulsion-blended fuels.

3.3. BTE

Figure 5 indicates the BTE variation with BP for test engines fuelled with BD, EBD5, EBD10, EBD15, and diesel. All fuels showed lesser BTE than pure diesel. Because of their decreased heating value, biodiesel and emulsified biodiesel blends are not as good for heating; diesel had a BTE of 30.2% at peak load of 4.4 kW as opposed to 28.7% for BD25, 28.2% for EBD5, 27.5% for EBD10, and 27% for EBD15. The primary reason behind the lower BTE occurs when blended fuels have a higher viscosity, which results in a minor heating system value.

The higher density and Viscosity tend to increase the fuel inline pressure with bulk modulus effect, leading to advanced injection of fuel inside the combustion chamber. The advanced Viscosity, which relates to the fuel, also causes poor atomization and requires more pumping energy. Hence, there is a decrease in brake thermal efficiency [12].

3.4. BSFC

The change in BSFC with brake power identified the tested engine fueled with BD, EBD5, EBD10, and EBD15 and diesel is shown in Figure 6. When W/D/BD fuel is ignited, it micro-explodes, increasing air and fuel mixing and increasing combustion efficiency.

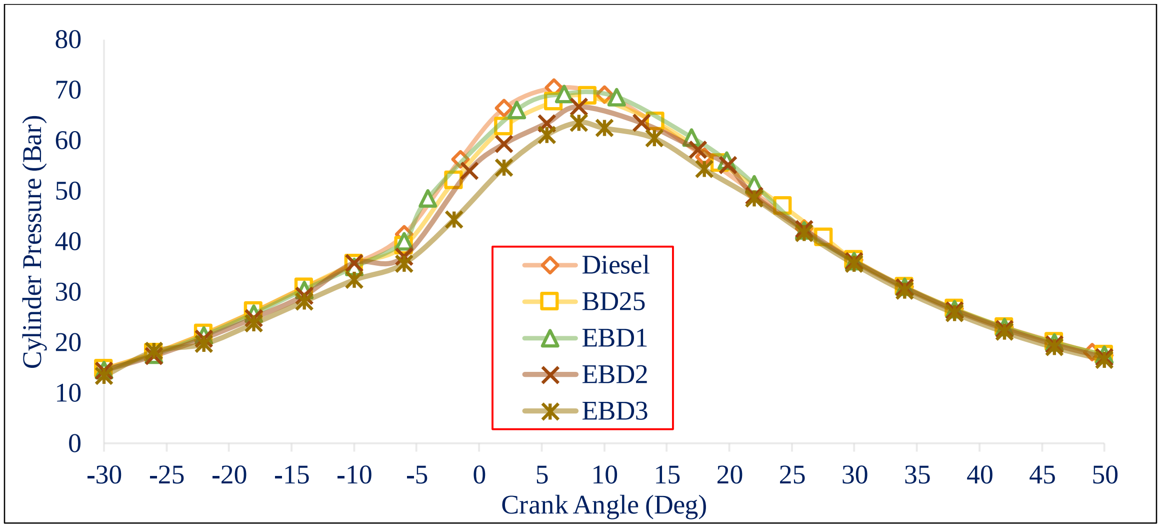

Fig. 4 Heat release rate vs CA

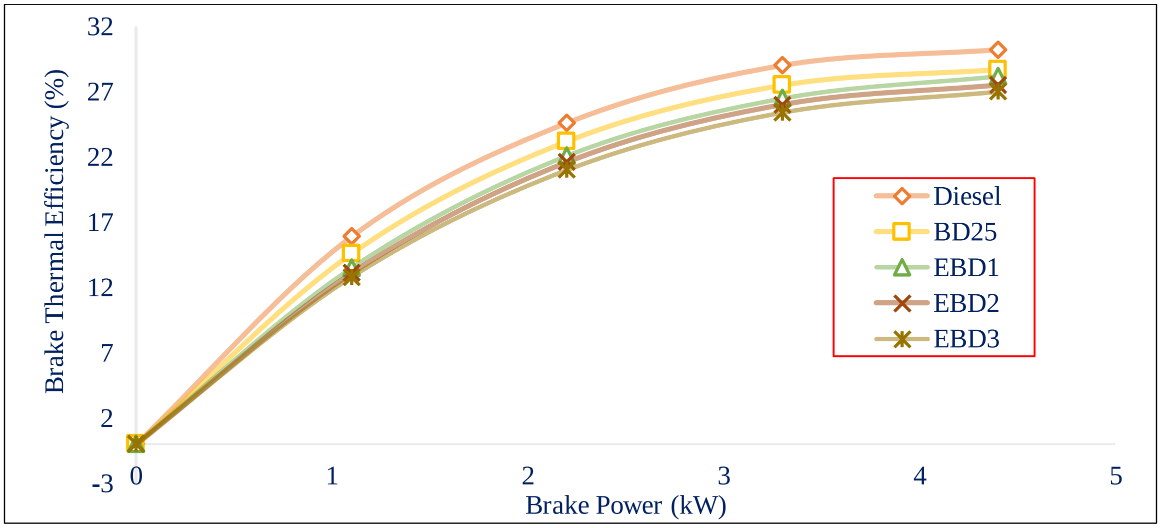

Fig. 5 BTE vs BP

The quick evaporation of liquid that is primarily present in an oil droplet causes the micro burst of W/D/BD, which is the secondary atomization of the initial spray. This process breaks the drop into tremendously fine particles and helps to progress the combustion.

All fuels displayed less BTE than the original diesel related to the minor heating of BD and emulsified biodiesel blends; diesel was found to have a BSFC of 0.25 kg/kW-K at the extreme power of 4.2 kW as compared to 0.25 kg/kW-h for BD25, 0.27 kg/kW-K for EBD5, 0.28 kg/kW-K for EBD10, and 0.29 kg/kW-K for EBD15. The main factors behind the decreased BTE with mixed fuels are advanced viscosity and minor energy satisfaction. Because of the advanced viscosity caused by the modulus effect, the fuel is injected into the combustion value earlier, which also tends to raise the fuel inline pressure [9].

The relative importance of factors like viscosity, density, volume-based fuel injection, and lower heating value affects the diesel engine's BSFC value. Because EBD5, EBD10 and EBD15 have lower heating values, more of them must be injected into different loads in order to make up for the fuel's chemical energy and attain higher loads.

3.5. EGT

Figure 7 represents the modification in EGT with BP for BD25, EBD5, EBD10, EBD15 and diesel. Water-biodiesel emulsions can help lower the peak combustion temperatures in the engine. This is because water has a higher heat capacity compared to biodiesel. This can help in mitigating NOx formation, as high combustion temperatures are a primary contributor to NOx emissions. It was observed that higher EGT through load owing to the increased fuel burning for higher loads.

At the average power of 4.2 kW, EGT of 302°C was obtained for diesel compared to 327°C with BD25, 313°C with EBD5, 292°C with EBD10 and 278°C with EBD15. The decreased EGT with emulsified blends is due to the higher hidden heat of water existing in EBD5, EBD10 and EBD15, which lowers the combustion temperatures. Also, the lower energy content of blended fuels resulted in lower EGT as compared to diesel [9].

3.6. CO Emission

Figure 8 displays the CO variation with BP for BD25, EBD5, EBD10, EBD15 and diesel with different loads. Incomplete fuel oxidation processes also contribute to the generation of CO, which is mainly driven by the comparatively delayed burning of smoke. CO is produced under the control of heterogeneous kinetics, principally throughout the last phase of combustion. There is no significant difference in CO emission experienced with low engine loads for diesel.

At the average power of 4.2 kW, CO emissions are 0.12 %vol. were obtained with diesel than 0.115%Vol. with BD25, 0.13%Vol. with EB5 and 0.14%Vol. with EB10 and 0.15% with EB15. The reduction in CO emissions for BD2 relates to excess O_2 present in the biodiesel, which promotes more oxidation.

Even though there is only a small increase in CO emission with blended fuels because of deterioration of combustion relates to higher hidden heat of water existing in the blend, which leads to high CO formation, the higher CO emission with EBD15 in maximum power is due to the occurrence of lower temperature combustion resulting in the dissociation of water molecules into OH radicals which react with carbon to form CO [7].

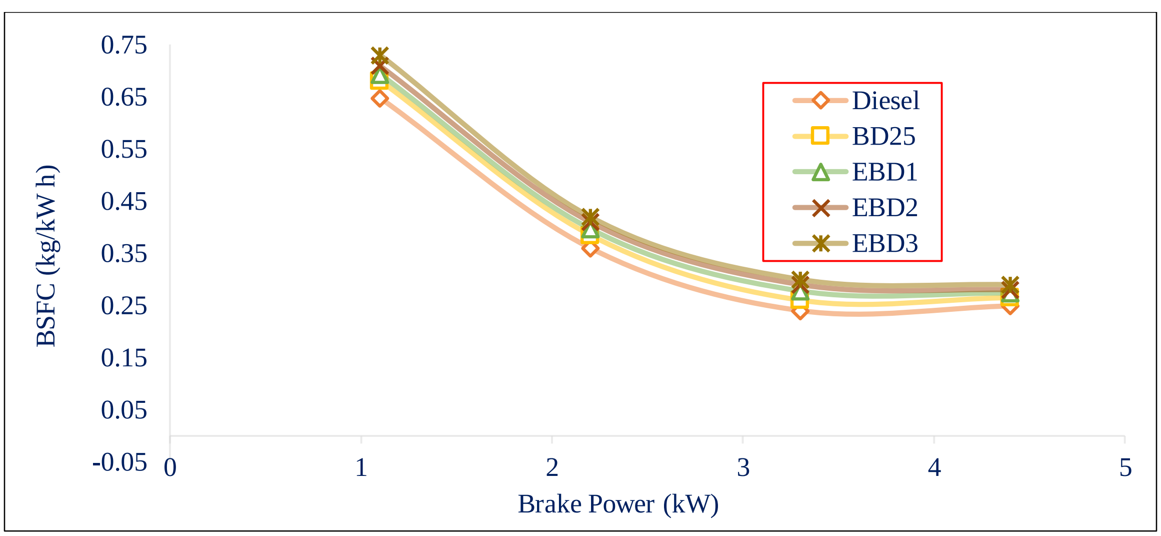

Fig. 6 BSFC vs BP

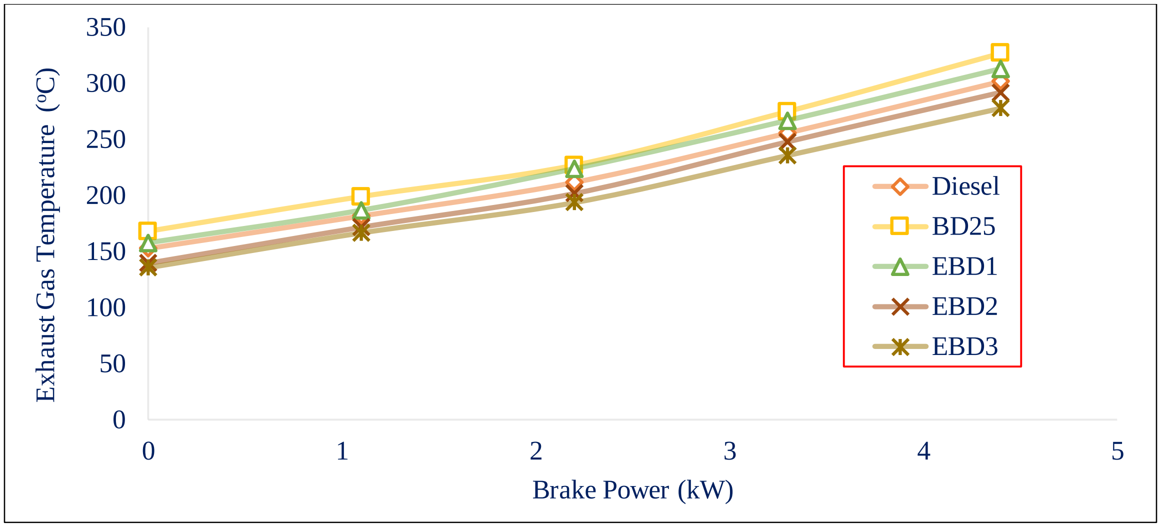

Fig. 7 EGT vs BP

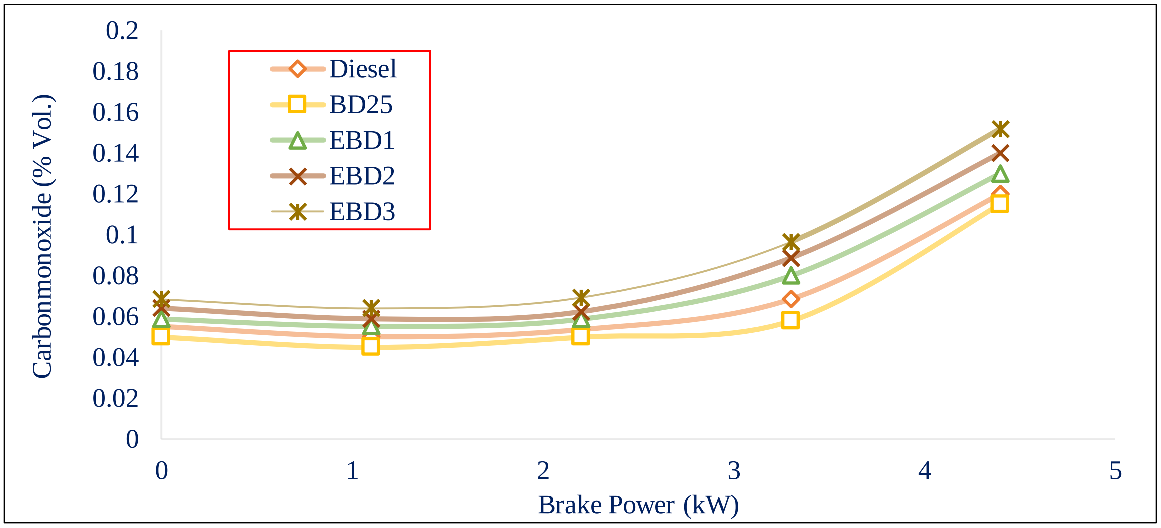

Fig. 8 CO emission vs BP

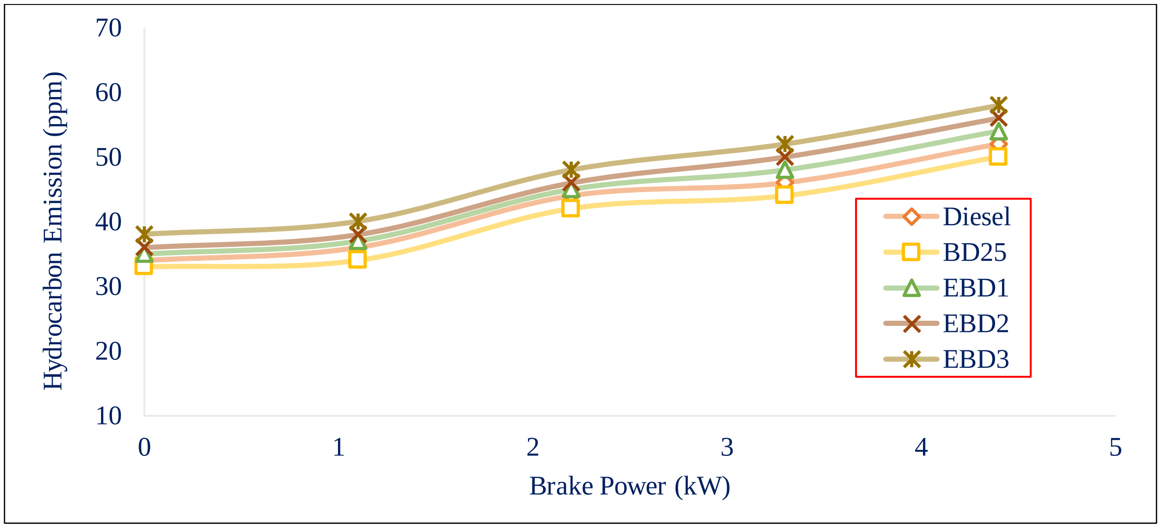

Fig. 9 HC emission vs BP

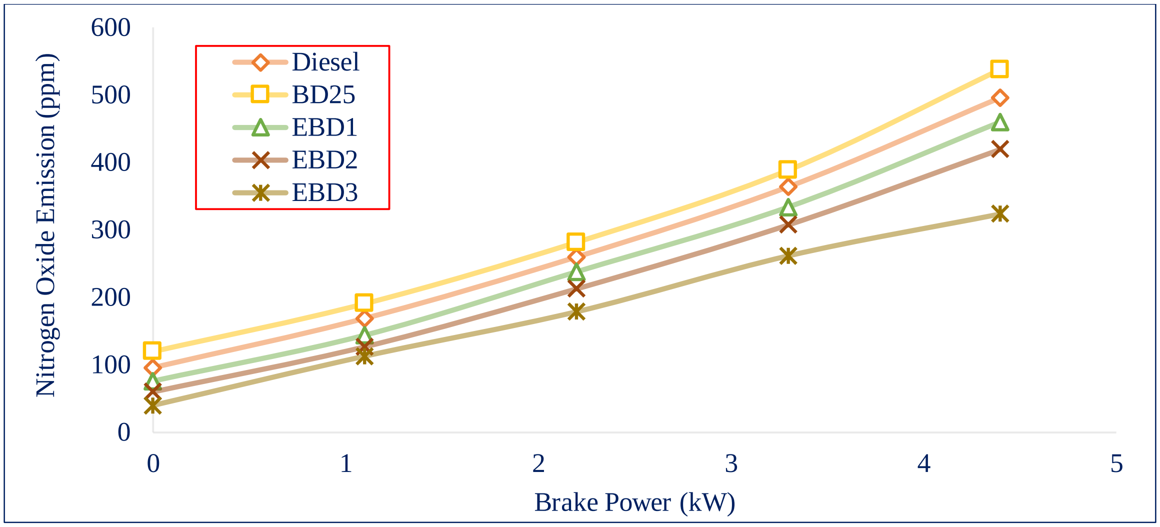

Fig. 10 NO emission Vs BP

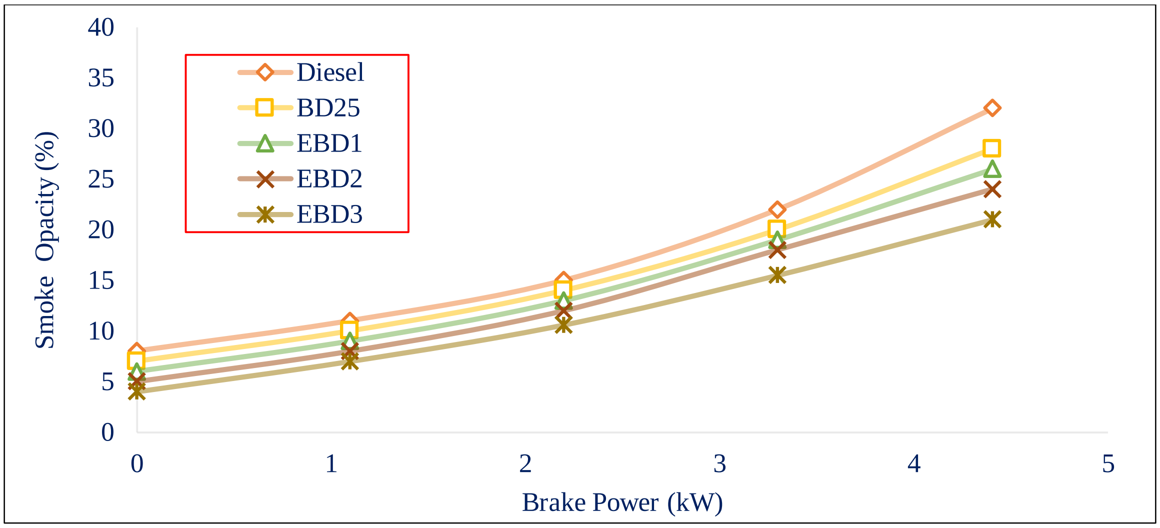

Fig. 11 Smoke opacity vs BP

3.7. HC Emission

Figure 9 illustrates the change in HC emission against BP for BD25, EBD5, EBD10, and EBD15. Diesel produced UBHC of 54 ppm at the maximum load of 4.4 kW, compared to BD25 is 50 ppm, EBD5 is 54 ppm, EBD10 is 56 ppm, and EBD15 is 58 ppm, correspondingly.

The presence of a satisfying layer of unburned oil in the burning chamber may be the cause of the increase in UBHC with blended fuels at lower engine loads. Additionally, the high thermal heat of water results in slower vaporization, and the mix of the fuel and air may have led to increased UBHC emissions.

Also, the higher viscosity and lower volatility of EBD5, EBD10, and EBD15 with lack of homogeneity causes higher UBHC emission. Due to a longer ignition delay, mixed fuel produces more UBHC emissions [7].

3.8. NO Emission

Figure 10 indicates the change in NO against BP for diesel, BD25, EBD5, EBD10, and EBD15. Nitrogen oxide emissions start to increase with the full load developed on the fuels, which could be related to higher in-cylinder temperature and nitrogen in the air [7]. Because of efficient combustion, NOx emissions increase with engine load increases.

BD25 emits more NOx than other blends in contrast with diesel under all engine maximum power circumstances. At the highest load of 4.2 kW, NO of 496 ppm was found for diesel, then 538 ppm for BD25, 460 ppm with EBD5, 420 ppm with EBD10 and 324 ppm with EBD15.

The NO was found to be lower with all combined fuels due to the higher hidden heat of vaporization of emulsions, which decreases the in-cylinder value. In addition, the occurrence of water in the micro-emulsion blends, which absorbs large amounts of heat for its evaporation, reduces the peak average temperature throughout the combustion and causes less NO emissions [13].

3.9. Smoke Opacity

The change in smoke opacity against BP with diesel, BD25, EBD5, EBD10, and EBD15 is shown in Figure 11. Partial Hydrocarbons (HC) and incomplete reactions of carbon molecules are the leading causes of smoke emissions, and a rise in HC with CO soot might rise smoke [14]. Because POME has lower carbon content and more enriched oxygen than diesel, it emits less smoke overall. At peak power conditions, BD25 shows a decline in smoke opacity of 20.6% compared to diesel. At the highest load of 4.2 kW, 32% smoke opacity was reported with diesel compared to 28% with BD25, 26% with EBD1, 24% with EBD2 and 21% with EBD3, which was due to the microburst of emulsified fuel which reduces soot formation in the combustion value and oxidizes the fuel-rich areas. In addition to this, the low C/H ratios and small fragrant fractions, together with the high oxygen content of the emulsion, result in lower levels of smoke with emulsified blends compared to diesel. Additionally, the increased spray volume, significant air through in the emulsion spray, and the micro-explosion event all contributed to the lowered smoke opacity with blended emulsified fuel at 4.4 kW [16].

4. Conclusion

The entire test was carried out on a diesel engine using diesel, BD25, and 5%, 10%, and 15% blends of water-emulsified biodiesel to investigate performance and emission behaviors. The outcomes were related to regular diesel fuel. The results are the inferences that can be made from the findings of the experiment.

- Based on the findings of the experiments, it can be said that biodiesel made from the Pongamia biodiesel blend is a good substitute for diesel and has the potential to encourage cleaner emissions, with the omission of NOx.
- It is reasonable to emulsify water with Pongamia biodiesel to decrease NOx and smoke emissions at the cost of a minor reduction in engine efficiency.
- Increased water content in emulsified biodiesel decreases BTE with increased BSFC at peak power. The BTE of EBD15 was decreased by 3.2%, and 1.7% for diesel and BD25, respectively.
- At peak power, the CO and HC of the emulsified biodiesel blends increased by 13-32%, and 8-16% respectively. The maximum increase in CO and UBHC for EBD15 is 32% and 16%, respectively. The extreme rise in CO and UBHC for EBD15 is 27%, and 12%, respectively, related to diesel.
- When related to BD25, the emulsified biodiesel blend EBD3 (BD25W15S1) results in a maximum reduction in NOx and Smoke soot of 40%, and 25%, respectively, at the outflow of a rise in CO and HC emissions of 32% and 16%. When related to diesel, the NOx and smoke soot from EBD3 were both reduced by 34%.
- Because water has a higher latent heat than the other tested fuels, the cylinder pressure and HRR for the EBD3 fuel dropped when compared to diesel and BD25.

In overall, it is suggested that the emulsified biodiesel fuel blend, which contains up to 15% water the blend, can be used in diesel engines to minimize NO and smoke emissions at the cost of slightly raising the fuel efficiency.

4.1. Future Work

The efficiency and emission measurement parameters of nanoemulsion fuels with varying water, biodiesel, and surfactant ratios are also rigorously assessed. Our research aims to identify the optimal water content in emulsions that achieves enhanced engine performance and reduced emissions, paving the way for environmentally conscious fuel choices. Additionally, we conduct a thorough economic analysis to gauge the potential viability of transitioning from conventional diesel fuel to emulsified biodiesel with water addition, shedding light on the economic implications of embracing sustainable fuel alternatives.

Acknowledgments

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