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The Performance and Emission Characteristics Assessment of Hybrid Biodiesel/Ethanol Blends in a Diesel Engine

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***Abstract* – In this study, a biodiesel blend was developed from the waste cooking oil methyl ester (WCOME) and soya bean oil methyl ester (SBME), namely, the optimum blend of WCOME-SBME (BM100) biodiesel. This biodiesel-biodiesel mixture (hybrid biodiesel) was in turn blended with 15 % of ethanol to give a biodiesel mixture-ethanol blend (BME15). The biodiesel-biodiesel mixture has a better density than the individual biodiesels, SBME had lower viscosity compared to BM100 and WCOME. The presence of ethanol in the hybrid biodiesel blend reduced both kinematic viscosity and the high density of the blend. BM100 also exhibited a better heating value compared to the individual biodiesels. Engine performance and emissions were tested using diesel (D100), WCOME, SBME, BM100, and BME15, and experimental results obtained compared with predicted using *Diesel-RK* software. The results indicated that at the maximum speed of 2500 rpm, BM100 performed better in terms of brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and brake mean effective pressure compared to the individual biodiesels (WCOME and SBME) but marginally poorer to D100. The BTE of BME15 is comparable to BM100. On the other hand, BME15 exhibited better emission characteristics having the lowest NO, particulate matter (PM), and hydrocarbon (HC) emissions compared to D100, WCOME, SBME, and BM100. Overall, when both engine performance and emission are considered BM100 increased engine performance compared to WCOME and SBME while BME15 is more effective in decreasing NO, PM, and HC emissions.**

***Keywords* – Assessment; diesel engine; Diesel-RK; hybrid biodiesel; prediction**

Nomenclature		
BP	Brake power	kW
BMEP	Brake mean effective pressure	bar
BSFC	Brake specific fuel consumption	g/kWh
BTE	Brake thermal efficiency	%
η_{th}	Brake thermal efficiency	%
NO	Nitric oxide	ppm
PM	Particulate matter	g/kWh
HC	Hydrocarbon	ppm

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1. INTRODUCTION

Energy consumption is ongoing due to lifestyle changes and population growth around the world. The use of fossil fuels to meet this energy demand has resulted in a serious challenge of fossil fuel reduction and an increase in fossil fuel prices.

In addition, the toxic compounds formed in smoke from these fuels have resulted in climate change, and significant environmental impacts such as an increase in greenhouse gas emissions, ozone layer depletion, deforestation, and acid rain [1]. The unsustainable and environmentally menacing impacts of fossil energy sources have necessitated the global quest for renewable energy options [2]. Therefore, a crucial search for alternative energy sources that are economically feasible, and environmentally friendly is needed [3], [4].

Currently, many scientists have focused their attention on alternative or substitute fuels such as biodiesel and its blends which are believed to reduce harmful emissions [5]. For biodiesel to be used as an alternative fuel in diesel engines, it must have characteristics like or the same as diesel fuel. Due to the production process and the feedstock, this is not possible. Hence, in most cases, biodiesel is blended with diesel or other additives. Biodiesel is known to have disadvantages of high density and viscosity. One of the techniques used to decrease the density and viscosity of biodiesel fuel is to blend it with alcohol to improve the fuel properties [6]–[8].

Alcohol has been described as a proper blend for biodiesel and diesel fuel to improve engine characteristics and decrease gas emission due to its high oxygen content [9]. Ethanol fuel has been regarded as a representative alternative fuel to biodiesel fuel. While biodiesel fuel is made of vegetable oil extracted from sunflower, soybean, palm, rapeseed, etc., ethanol fuel is made of glucose derived from starch crops such as sugarcane, wheat, and corn. Both fuels are also environmentally friendly and always renewable since they are of plant origin [10].

Due to the debate on the conflict between food and biofuels, some researchers have expressed their preference for biodiesel production from hybrid feedstock and the use of hybrid biodiesel (biodiesel mixture). They opined that such combinations also enhance the fuel-related properties of biodiesel [11]. However, while many studies have been carried out on the use of hybrid feedstock in biodiesel production, quite a few have been done on the combustion, performance, and emission characteristics of the biodiesel-biodiesel mixture (hybrid biodiesel).

Most of the studies from the available works from literature have focused on performance, combustion, and emission characteristics using biodiesel-alcohol blends and biodiesel-diesel-alcohol blends to reduce the limitations of high density and viscosity and improve fuel properties.

The influence of biodiesel-ethanol blends on performance and emissions at various proportions using diesel engine at a fixed speed of 1500 rpm and different loads were evaluated and compared by [12]. The results indicate that the BTE of biodiesel-ethanol blends increases along with engine load compared to diesel due to the low viscosity of alcohol blends. It was also observed that the BSFC of the biodiesel-ethanol blend increased compared to diesel due to its low heating value.

An experimental investigation on the performance and emission characteristics of a diesel engine fuelled with biodiesel and its ethanol blends (5 %, 10 %, and 15 %) at a constant speed and various load conditions was conducted by [13]. The results showed that the BSFC of biodiesel-ethanol blends increased compared to biodiesel due to low heating value. The BTE of diesel engines fuelled with biodiesel-ethanol blends was low compared to diesel fuel at low load conditions, and this could be explained by the low combustion temperature and high

latent heat of evaporation of ethanol blends. The CO and HC emissions of biodiesel-ethanol blends were high compared to diesel, while its NOx emissions decreased.

An investigation on the impact of biodiesel-ethanol blends and biodiesel-methanol blends on diesel engines under different load conditions showed that the BSFC of the diesel engine powered by the biodiesel-ethanol blend was lower compared to the biodiesel-methanol blend but higher than diesel due to the high latent heat of vaporization of alcohol blends [14].

From the results of the comparison on performance and exhaust gas emission for a diesel engine powered with biodiesel and ethanol fraction blends, it was found that the BSFC of the engine fuelled with ethanol blends was higher than for neat diesel due to high density and viscosity. High HC emissions were noticed with ethanol blends compared to diesel due to the formation of a quenching layer of unburned ethanol inside the combustion chamber which might have escaped from the combustion zone [15].

Literature search has shown that several researchers have conducted experiments with the blends of single biodiesel but only a few studies might have been done on biodiesel-biodiesel blend [16] and a ternary mixture of biodiesel-biodiesel-alcohol. Therefore, the objective of this study is to assess the performance and emission characteristics of ternary blends of biodiesel mixture and ethanol (biodiesel-biodiesel-ethanol). Also, to have a better understanding and reduce costs incurred during experiments, *Diesel-RK* software was used, and the results obtained were compared with experimental and/or data analysis from experimental results. The engine performance characteristics studied were BP, BSFC, BTE, and BMEP while NO, PM, and HC were the emission characteristics.

2. MATERIALS AND METHODS

2.1. Biodiesel Production and Blending

Neat biodiesel fuels (WCOME and SBME) were produced from waste cooking and soya bean oil respectively, by transesterification using methanol as a reagent and NaOH as a catalyst. These biodiesels were produced to meet the standard of ASTM 6751, and the ethanol with a degree of purity of 99.9 % which meets the standard of ASTM D5798 was purchased from local dealers. The neat biodiesel fuels were blended with each other at room temperature to produce the optimum blend of waste cooking oil-soya bean (BM100) biodiesel or hybrid biodiesel. The hybrid biodiesel was in turn blended with 15 % of ethanol to give a biodiesel mixture-ethanol blend (BME15). During mixing, the fuels were stirred continuously for uniformity at room temperature and pressure. After the blending process, the blends were stored in a brown bottle to prevent oxidation with ambient air and were used within one-day [10].

2.2. Properties of Fuels Used

Fuel properties are known to have significant impacts on engine performance, combustion parameters, and emission characteristics. The properties of fuel samples used in this study, i.e., diesel (D100), waste cooking oil methyl ester (WCOME), soya bean oil methyl ester (SBME), biodiesel mixture (BM100), hybrid biodiesel-ethanol blend (BME15) (15 % ethanol and 85 % BM100) were tested using the ASTM procedure and are presented in Table 1.

TABLE 1. FUEL PROPERTIES

Properties	D100	WCOME	SBME	BM100	BME15
Density, kg/m³	0.8263	0.8868	0.8865	0.8857	0.8714
Viscosity at 40 °C, mm²/s	2.66	4.72	4.238	4.411	3.255
Heating value, MJ/kg	42.5	37.5	39.6	41.5	36.2
Flash Point, °C)	78.5	193	130	150	90.5

3. ENGINE TEST SETUP

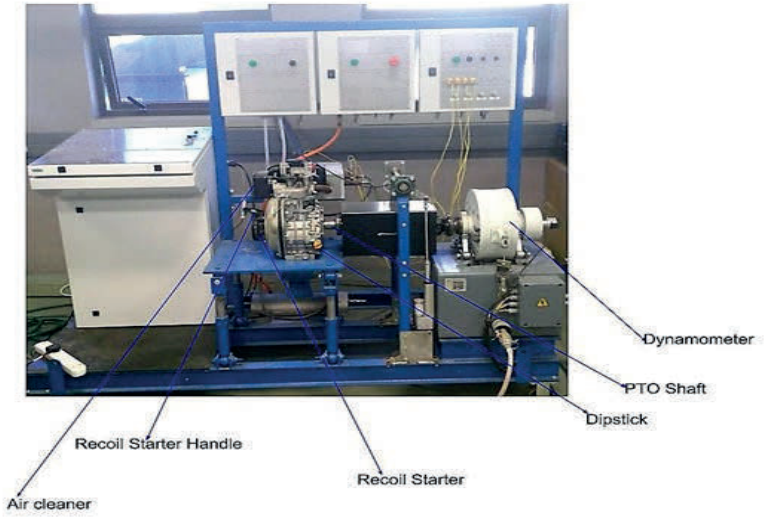
3.1. Set Up and Experimental Procedure

The experimental aspect of the study was carried out using a single-cylinder, compression ratio (CR = 17), four-stroke, diesel engine, and at full load conditions whose output shaft was linked to an eddy current dynamometer to measure the speed, brake power, and brake torque. The experiments were performed at different engine speeds ranging from 1000, 1500, 2000, to 2500 rpm. The detailed specifications of the engine setup are presented in Table 2 while the engine test setup is shown in Fig. 1(a) and (b).

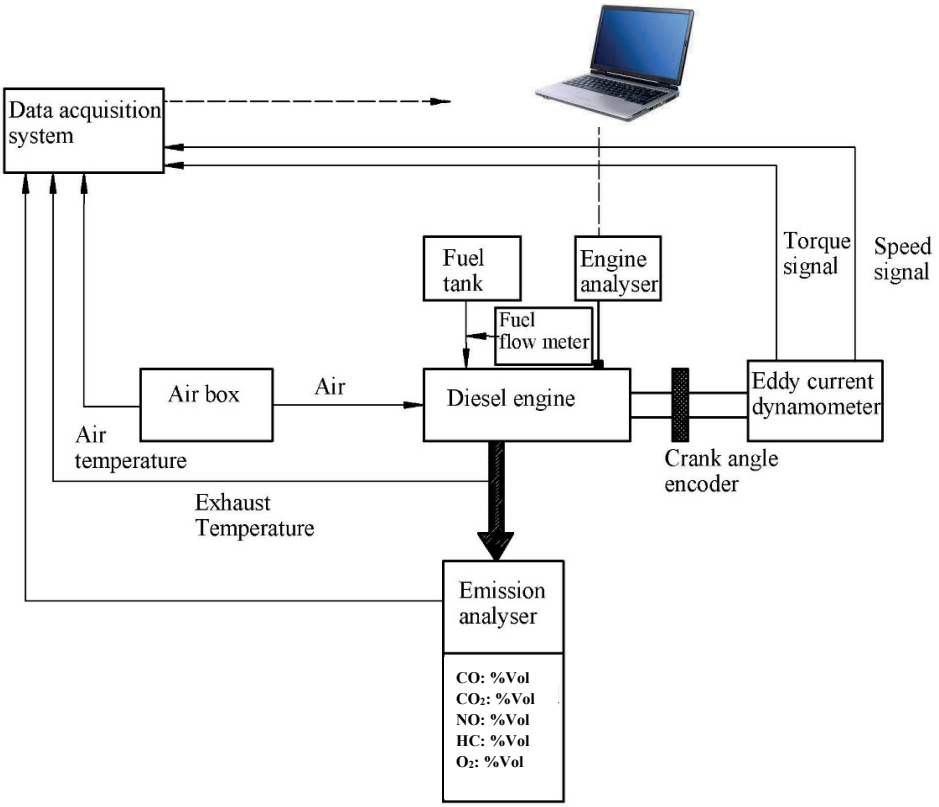
The X-Tract Extreme, a generic engineering software platform that measures, stores, displays, and controls, based on the measurement of physical signals such as speed, torque, power, temperatures, pressures, fuel flow, airflow, and emissions was used. The engine was warmed up for about 20 minutes using 100 % diesel fuel after which the fuel line was switched to WCOME, SBME, BM100, and BME15, respectively, and the engine speed was adjusted according to the test programme. During each engine test run, sampling and measurement of the different parameters were carried out. After each fuel was tested, the engine was run on pure diesel to clean the fuel line before testing another. From the measured parameters and data analysis, computation of the performance and emission characteristics was carried out, and the results obtained were compared with the simulation using *Diesel-RK* simulation software.

TABLE 2. TECHNICAL DESCRIPTIONS OF DIESEL ENGINE

Specification	Description
Model	L48N6CF1T1AA
Type	4 Stroke, diesel engine
No. of cylinders	1
Rated power	3.5 kW@3600 rpm
Bore	57 mm
Stroke	70 mm
Injection systems	Direct injection



(a)



(b)

Fig. 1. Engine test setup: a) photographic; b) schematic.

3.2. Uncertainty Analysis

Faults may be an unavoidable in the course of using experimental equipment. Therefore, it is crucial to measure the uncertainty evaluation of the test method to expand the accuracy results. However, the evaluation was conducted three times to expand the accuracy of the results obtained.

Using the percentage uncertainties of various instruments, we determined the percentage uncertainties of the different parameters measured. The accuracy and uncertainties of the measured and calculated parameters in this study are presented in Table 3. Using the principle of propagation of errors, the total percentage of uncertainty for the measured and calculated parameters is as follows [17]:

$$\%T_{\text{un}} = \sqrt{un_{\text{BP}}^2 + un_{\text{BSFC}}^2 + un_{\text{BTE}}^2 + un_{\text{BMEP}}^2 + un_{\text{NO}}^2 + un_{\text{HC}}^2} = \pm 3.2\ \%\,, \tag{1}$$

where

T_{un} total of uncertainty;
un_{BP} uncertainty of brake power;
un_{BSFC} uncertainty of brake specific fuel consumption;
un_{BTE} uncertainty of brake thermal efficiency;
un_{NO} uncertainty of oxide emissions;
un_{HC} uncertainty of unburnt hydrocarbon emissions.

TABLE 3. UNCERTAINTIES OF THE PARAMETERS

Measurements	Instrument	Type	Range	Accuracy	Uncertainty, %
BP	–	–	–	–	±3.0
BSFC	–	–	–	–	±2.5
BTE	–	–	–	–	±2.3
BMEP	–	–	–	–	±2.0
NO		Bosch BEA060	0–5000 ppm vol	±1 ppm vol	±0.5
HC		Bosch BEA060	0–9999 ppm	±1 ppm vol	±0.1

4. NUMERICAL MODELLING

The numerical study was carried out at full load conditions, constant compression ratio (CR) of 17, and various engine speeds. A four-stroke, single-cylinder diesel engine model was loaded into *Diesel-RK* software, and fuel properties such as viscosity, density, and calorific value were used to perform the simulation. *Diesel-RK* is a modelling and simulation software used to analyse internal combustion engines. The *Diesel-RK* software uses a multi-zone fire model based on the mixture and combustion model of Razleisev and developed by Kuleshov (Razleisev-Kuleshov model or RK model [18]. The RK model has considered the parameters affecting the process of mixture creation and burning of the diesel engine in detail, such as fuel supply law, the shape of the combustion chamber, shape and distribution of spray, the intensity of tangled movement in the cylinder, the impact of spray with the combustion chamber surface, and the interaction between adjacent sprays. The parameters which were computed to determine the performance of the diesel engine using *Diesel-RK* software were brake power, brake specific fuel consumption, brake thermal efficiency, and brake mean effective pressure whereas the emissions were NO and PM emissions. These parameters were computed for each fuel and at different engine speeds. The software was set to predict the engine characteristics of the fuel blends and compared with D100 as a reference fuel.

Brake power is given by the product of brake torque and rotational speed:

$$BP = T \cdot \omega (\text{kW}), \tag{2}$$

where T is brake torque, Nm, and ω is rotational speed, rpm.

Brake specific fuel consumption is the amount of fuel consumed per unit of power produced, that is:

$$BSCF = \frac{\dot{m}_f}{BP} (\text{g/kWh}), \tag{3}$$

where $\dot{m}_f$ is fuel mass flow rate, kg/s, BP is brake power, kW.

The brake thermal efficiency was evaluated from the brake-specific fuel consumption and heating value:

$$\eta_{\text{th}} (\%) = \frac{BP}{\dot{m}_f (HV)} \cdot 100, \tag{4}$$

where HV is the heating value, J/kg.

The brake mean effective pressure is a measure of power produced per cycle as a function of engine size:

$$BMEP = \frac{BP}{V_c \omega} (\text{bar}), \tag{5}$$

where

BP brake power, kW;
ω angular crank velocity, rpm;
V_c clearance volume, m^3.

The concentration amount of NO from combustion formed through the recent computation stage obtained from [19]:

$$\frac{\text{d}[NO]}{\text{d}\theta} = \frac{p \cdot 2.333 \cdot 10^7 \cdot e^{-\frac{38020}{T_Z}} [N_2]_e \cdot \left(1 - \left(\frac{NO}{[NO]_e}\right)^2\right)}{R \cdot T_Z \cdot \left(1 + \frac{2365}{T_Z} \cdot e^{\frac{3365}{T_Z}} \cdot \frac{NO}{[O_2]e}\right)} \cdot \frac{1}{\omega}, \tag{6}$$

where

P in-cylinder pressure, Pa;
T_Z cylinder temperature of the burnt gas, K;
R gas constant, J/(mole·K);
ω angular crank velocity, rpm.

Datta and Mandal [20] demonstrated the computation of PM emission as a function of Bosch smoke number described as:

$$[PM] = 565 \left(In \frac{10}{10 - Bosch} \right)^{1.206}. \tag{7}$$

5. Results and Discussions

5.1. Fuel Properties

From the experimental fuel properties of WCOME, SBME, BM100, BME15, and D100, (Table 1), the densities of all biodiesel fuels are close to each other. The maximum difference between the properties of the individual biodiesel fuels and BM100 range from 0.12 % for density to 6.5 % for viscosity. While BM100 showed better density than the individual biodiesels, SBME had lower viscosity compared to BM100 and WCOME. BM100 also exhibited a better heating value than the individual biodiesel fuels. Except for heating value and flash point, the hybrid biodiesel-ethanol blend (BME15) showed better density and viscosity properties. The comparison easily shows the improvement of some properties. This indicates that the blend of two biodiesels and its ethanol additive improved fuel properties.

5.2. Brake Power

Fig. 2 shows the BP of the blends of the biodiesels and D100 operating at full-loading conditions. At a maximum speed of 2500 rpm, among the green fuels, BM100 shows the highest brake power while BME15 shows the least power. Biodiesel fuels have a high cetane number and this might have led to the high performance at high speed. Also, the high calorific (heating) value (CV) of BM100 compared to the individual biodiesel fuels might be the reason for higher BP. The low value of BP for BME15 might be due to its low heating value. Also, the low cetane number of ethanol might have impacted on the hybrid biodiesel-ethanol blend leading to low output power. Similar results have been reported by [21], [22] in the literature. D100 exhibited better BP performance than all the test fuels. The experimental results obtained were compared with predicted using the *Diesel-RK* simulation software. The results show that at 2500 rpm, the difference between the predicted and experimental ranged from 2.17 % to 4.12 % with the predicted values having higher values than the experimental.

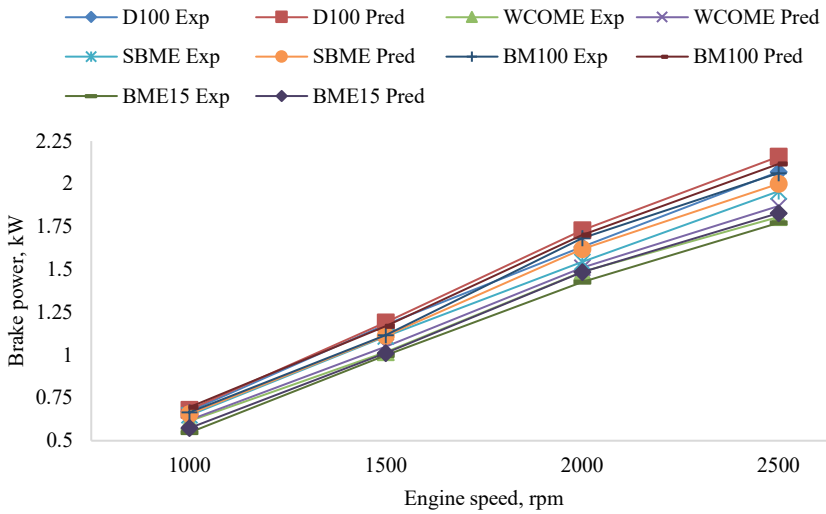


Fig. 2. Variation of brake power with engine speed.

5.3. Brake Specific Fuel Consumption

Fig. 3 illustrates the BSFC of the biodiesel blends and D100 at different engine speeds. At lower speeds, all the test fuels show slightly higher BSFC. At the maximum speed, the BSFC in the order: BME15 (319 g/kWh), WCOME (313 g/kWh), SBME (292 g/kWh), BM100 (276 g/kWh), and D100 (271 g/kWh). This followed the trend of the values of the CVs in Table 1 where BME15 had the lowest CV and D100, had the highest. The low CVs of the biodiesels might be the cause of the increment of BSFC compared to D100. The increase in BSFC of BME15, WCOME, SBME, and BM100 might be due to the high volume of fuel consumed to generate the required amount of energy. Another reason for this increase was due to high latent heat of evaporation as the heat was lost from the combustion chamber due to evaporation of the cooling effect. Similar results were reported by [23]. However, at high speeds, the high combustion temperatures and additional oxygen contents of the biodiesels enhance combustion performance and reduce BSFC. Generally, the increase in BSFC has been attributed to the lower calorific value of biodiesel, and possibly higher density compared to diesel fuel. It has also been observed that the atomisation ratio and injection pressure have some effects on brake specific fuel consumption [24]. But it is not well understood why the additional oxygen content from ethanol did not reduce the BSFC of BME15 compared to all the other test fuels. At a maximum speed of 2500 rpm, the results obtained using the *Diesel-RK* software were marginally higher than those obtained from the data analysis of experimental results.

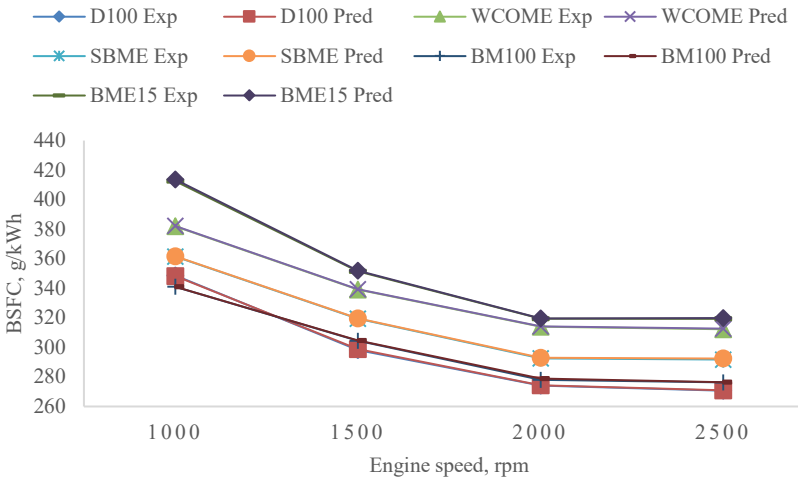


Fig. 3. Variation of brake specific fuel consumption with engine speed.

5.4. Brake Thermal Efficiency

The brake thermal efficiency characteristics of the tested fuels at different engine speeds are shown in Fig. 4. The test results show that for all the test fuels the BTE increases with increasing engine speed. At high speed, the biodiesel-biodiesel mixture (BM100) shows higher thermal efficiency (31.4 %) than the individual biodiesels while the BTE was lowest for WCOME (30.7 %). The high brake power of BM100 led to the high brake thermal efficiency. Due to the combined effect of reduction in heating value, higher viscosity, higher density, and increase in

fuel consumption, the BTE of WCOME, SBME, and BME15 blends are marginally lower at maximum when compared to diesel (31.3 %). The high BTE of the hybrid biodiesel and hybrid biodiesel-ethanol blend may be attributed to the better atomisation during injection and the reduction in friction loss associated with higher lubricity. Also, BME15 has increased oxygen content from ethanol which should improve combustion, hence a high BTE of 31 % at the maximum speed. At the same operating conditions, *Diesel-RK* predicted lower results compared to those obtained from the analysis of the experimental data.

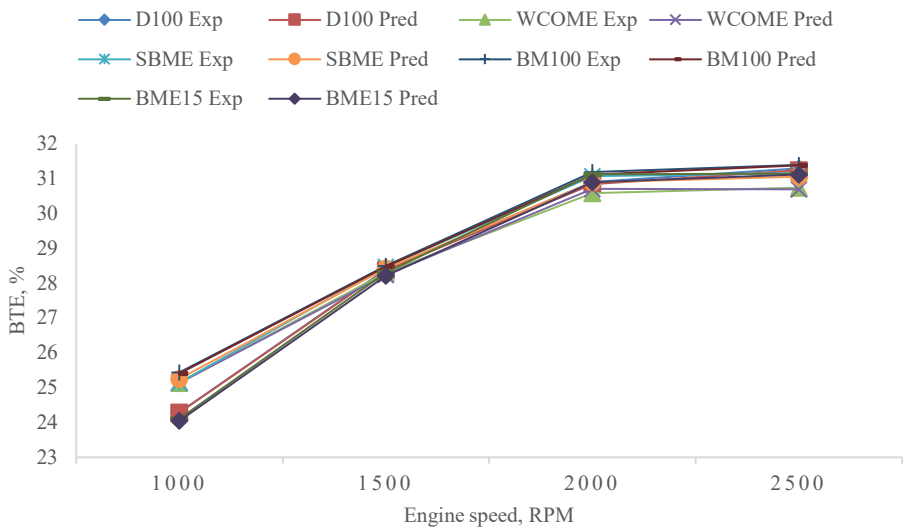


Fig. 4. Variation of brake thermal efficiency with engine speed.

5.5. Brake Mean Effective Pressure

The variation of BMEP with engine speeds for D100, WCOME, SBME, BM100, and BME15 is shown in Fig. 5.

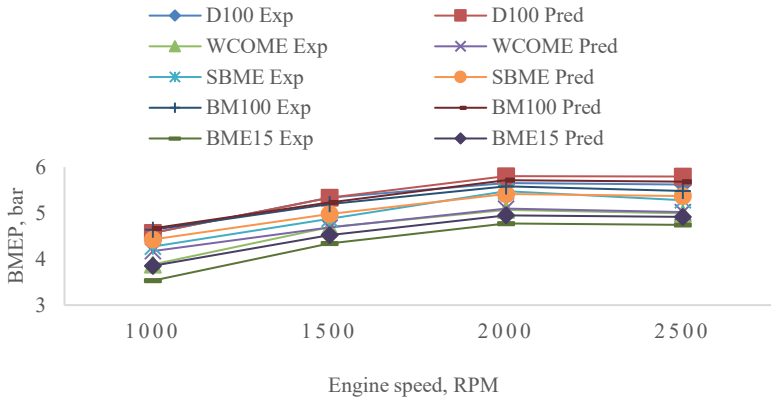


Fig. 5. Variation of brake mean effective pressure with engine speed.

The results show that among the biodiesel fuels, BM100 exhibited the highest BMEP value while BME15 had the lowest. D100 had the highest value among all the tested fuels. The lower values of BMEP for the biodiesels compared to D100 has been explained to be due to the low heating values of pure biodiesels, hybrid biodiesel, and ethanol blend. Similar results were reported by [25]. The predicted values of BMEP using the *Diesel-RK* software gave errors ranging from 0.5 % to 3.6 % when compared to results obtained from analysis of the experimental values. Nonetheless, both the predicted and experimental followed similar trend of BMEP variation with engine speed.

5.6. NO Emissions

Fig. 6 depicts the NO emissions of the test fuels at different engine speeds. The results show that NO emissions obtained from both the experimental and predicted data reached a maximum and decreased for all test fuels. At all engine speeds, the experimental and predicted values of NO emissions for BME15 was the lowest compared to the individual biodiesels and diesel. This agrees with other results found in the literature for biodiesel-ethanol blends [9], [26]. The reason for this reduction is perhaps due to low in-cylinder combustion temperature, owing to heat of vaporization of ethanol. An increase in speed (load) leads to more energy to vaporize ethanol, which improves the combustion, and results in a higher combustion temperature and lower NO emissions. Among the biodiesels, BM100 exhibited the highest value of NO emissions. Even though the maximum error (14.5 %) between the predicted and experimental was recorded for WCOME, the curves followed similar trends.

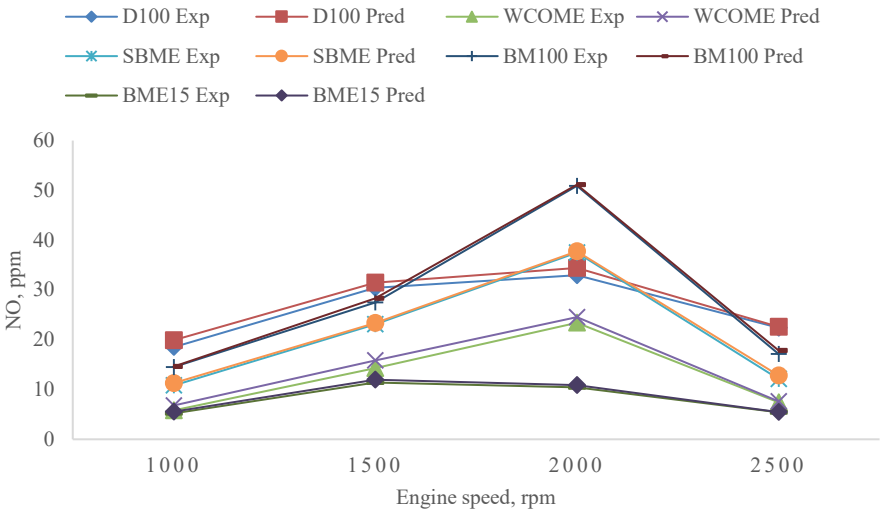


Fig. 6. Variation of NO emissions with engine speed.

5.7. Particulate Matter Emissions

Fig. 7 shows the results of PM emissions predicted with *Diesel-RK* software at different engine speeds as the exhaust gas analyser lacked the capacity to analyse PM. The predicted results showed that the PM emissions of all the fuels tested decreased with an increase in engine speed. Except at 1000 rpm, D100 emitted more PM than the rest of the fuels. At all engine speeds, BM100 and

BME15 showed lower emissions when compared to the individual biodiesels and diesel fuel. This result agrees with [27] and [28] who studied the emission of biodiesel-ethanol blended fuels and reported that the biodiesel-ethanol blended fuel has a lower PM emission.

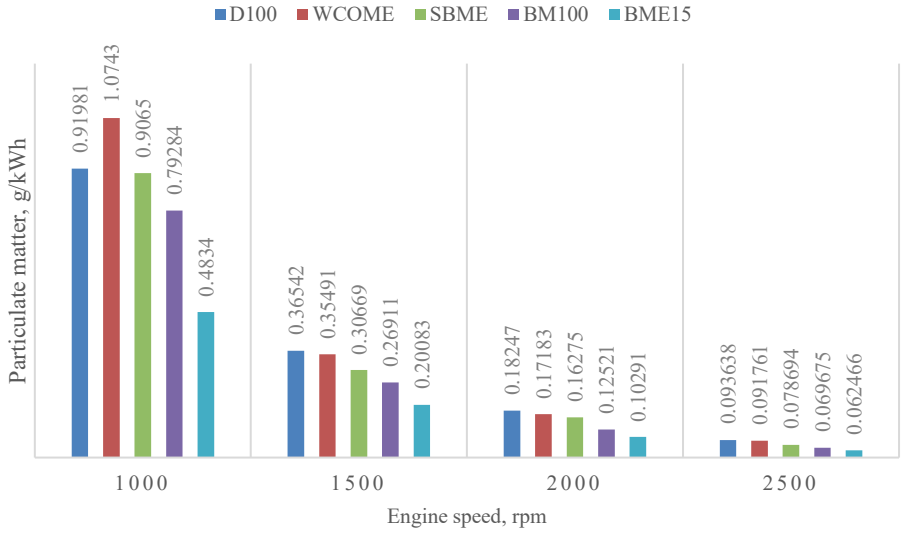


Fig. 7. Variation of particulate matter emissions with engine speed.

5.8. Hydrocarbon Emissions

The experimental results of the variation of HC emissions at different engine speeds are shown in Fig. 8.

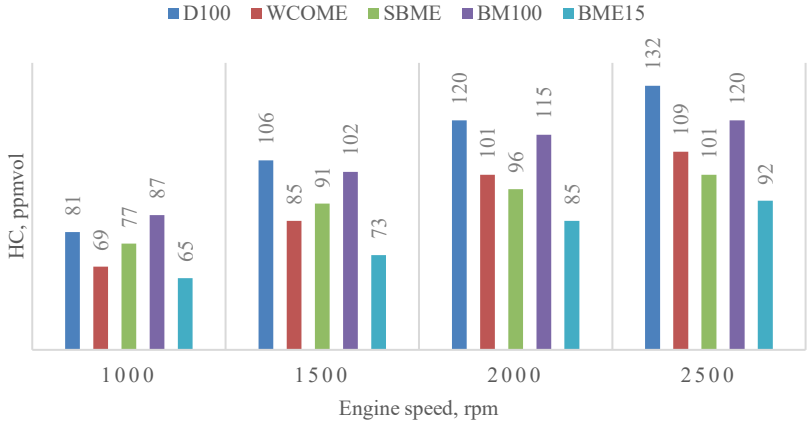


Fig. 8. Variation of hydrocarbon emissions with engine speed.

The results showed that except at 1000 rpm, D100 had the highest values of HC emissions compared to other fuels tested. In all cases, BME15 recorded the lowest HC emissions. At lower

engine speeds, HC emissions were lower for WCOME compared to SBME and BM100. Some researchers also reported that the HC emissions of diesel fuel was higher than biodiesel and alcohol blends [9], [13]. The high oxygen content of biodiesel leads to better combustion which gives low HC emissions. However, results obtained by some researchers have shown that at full loads, due to factors such as ignition delay, fuel mixing, spray pattern, and measuring equipment response, the HC emissions for biodiesels exhibit higher HC than that of diesel [16], [29].

6. CONCLUSION

The biodiesel-biodiesel mixture has a better density than the individual biodiesels, SBME had lower viscosity compared to BM100 and WCOME. The addition of ethanol in the hybrid biodiesel blend reduces both kinematic viscosity and the high density of the blends. BM100 also exhibited a better heating value compared to the individual biodiesels. The results of the engine performance and emission characteristics of the fuels which were assessed experimentally and analysed from measured data and *Diesel-RK* software showed that compared to the individual biodiesels (WCOME and SBME), BM100 exhibited better engine performance in terms of brake power, brake specific fuel consumption, brake thermal efficiency, and brake mean effective pressure while BME15 had a comparable BTE with BM100. In terms of emissions, BME15 showed the lowest values of NO, PM, and HC. The *Diesel-RK* software resulted in higher predicted values than the experimental, but the curves followed similar trends. Therefore, considering the experimental and predicted results obtained from this study, it is concluded that the blend of two biodiesels and its ethanol additive improved some fuel properties and engine performance and emission characteristics of the tested fuels.

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