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Comparative Experimental Study on the Effects of Biodiesel Mixture with Ethanol and Butanol Blends on Performance and Emission Characteristics of a Diesel Engine Generator

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Abstract **– The depletion of fossil fuels, increasing gas emissions and fuel consumption have created a massive need for alternative fuels. Biodiesel is known to have high density and viscosity, which makes it challenging to use in diesel engine generators. One of the methods that can be used to decrease the density, viscosity and emission characteristics is to blend with percentage alcohols. A biodiesel mixture (BDM100) made from waste vegetable oil (WVO) and soybean oil (SBO) has shown some potential in this study. The biodiesel mixture was formed by blending with 15 % ethanol and 15 % butanol, resulting in a biodiesel mixture-ethanol blend (BMET15) and biodiesel mixture-butanol blend (BMBT15). The purpose of this study is to thoroughly evaluate and compare a diesel engine generator's performance and emission characteristics powered by diesel fuel (D100), BDM100, BMET15, and BMBT15. The experiments were carried out on a single-cylinder diesel engine generator at different speeds. The results indicated that the brake power (BP) of BDM100, BMET15, and BMBT15 decreased by 1.9 %, 17.8 %, and 16.0 % compared to D100. The brake-specific fuel consumption (BSFC) of BDM100, BMET15, and BMBT15 increased by 2.0 %, 17.8 %, and 19.1 % compared to D100. The BDM100 and BMET15 offer 0.4 % and 2.9 % more brake thermal efficiency (BTE) than D100 at maximum speed. The BDM100, BMET15 and BMBT15 decreased hydrocarbon (HC) by 4 %, 26.4 % and 28.8 %, whereas carbon dioxide (CO_2) decreased by 9.7 %, 32.4 %, and 28.5 %; Bosch Smoke Number decreased by 21.2 %, 38.1 %, and 29.9 % compared to D100.**

Keywords **– Biodiesel; emissions; experimental; fuels; performance.**

Nomenclature

BP	Brake power	kW
BSFC	Brake-specific fuel consumption	g/kWh
BTE	Brake thermal efficiency	%
HC	Hydrocarbon	ppm
BSN	Bosch smoke number	–
D100	Diesel fuel	–
BDM100	Biodiesel mixture	–
CO_2	Carbon dioxide	g/kWh

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BMET15	Biodiesel mixture-ethanol blend	–
BMBT15	Biodiesel mixture-butanol blend	–
WVOB	Waste vegetable oil biodiesel	–

1. INTRODUCTION

Biodiesel is a sustainable alternative fuel for diesel engines since it can be broadly available and renewable. Prior research has indicated that the blending of biodiesel with diesel results in increased fuel consumption and nitrogen oxide (NO_x) emission, reduced emission of carbon monoxide (CO), unburnt hydrocarbon (HC) and particulate matter (PM) [1], [2]. However, the high density and viscosity of biodiesel affect the performance and combustion quality [3], [4]. The fuel properties can be enhanced by blending biodiesel with alcohols such as ethanol and butanol [5], [6]. Butanol increases the energy content and number of kilometres that may be driven on a single fuel litre. Ethanol's high oxygen content enhances combustion and reduces CO emissions, and its simplicity of blending makes it a widely accessible and commonly used biofuel. NO_x is recognized to be the primary source of pollution, acidic rain, and atmospheric ozone [7]. Soot emissions may be the primary cause of lung cancer and a contributing factor to the development of cardiovascular diseases over an extended period of time [8]. Moreover, the leading cause of greenhouse gasses and global warming is CO_2, one of the leading gas emissions from vehicles.

Researchers and industries have been under pressure to find sustainable energy sources due to the growing concern over the scarcity of fossil fuels and the rising demand for fuel over the past few decades. Biodiesel and alcohol blends are renewable fuels that have received much attention and have significant potential for use in diesel engines.

According to [9], [10], biodiesel is a fatty acid alkyl ester molecule produced through the chemical interaction of vegetable and animal oils with alcohol. It occurs when alcohol (ethanol-methanol) and a catalyst (potassium hydroxide-sodium hydroxide) react with the unprocessed product used for biodiesel (oil). Fatty Acid Methyl Ester (FAME), or biodiesel, is the end product. Common processes for producing biodiesel include pyrolysis, microemulsion, transesterification, and dilution.

Since they have larger molecular weights, biodiesel fuels are less compressible and have a higher density and viscosity than standard diesel fuels. Density and viscosity have an impact on the quantity of fuel supplied to the engine. Significant issues include droplet size and atomization quality, particularly at high loads [11], [12]. In diesel cycle engines, biodiesel can be used pure or in blend. Since it may be used as engine fuel without modification and has a high cetane number, thermal value, and lower exhaust emission value, it is favoured as an alternative fuel. Vegetable oils and waste oils are the main sources of biodiesel. It's a cost-effective fuel that can replace diesel fuel and is safer for the environment. According to [13], it is also a beneficial fuel for eliminating waste oil's harmful environmental effects.

The direct application and blend of biodiesel are sufficient without requiring engine modifications. A primary fuel can be added to mixtures to overcome issues with using pure or highly biodiesel mixtures because of its reduced density, viscosity, and improved fluidity [14].

The hydroxyl (OH) atoms found in alcohol molecules result in clean fuels that may be blended with biodiesel and diesel. The use of vegetable oils in diesel engines is made possible by their low viscosity and density. The engine brake power and brake-specific fuel consumption are enhanced when a blend of alcohol and biodiesel is used instead of using biodiesel alone [15]. Nitric oxide and carbon dioxide emissions increased, but hydrocarbon and carbon monoxide emissions decreased [16].

Diesel engines powered by standard diesel fuel emit emissions that negatively impact the environment and human health. Developed nations want to discover innovative, affordable, and ecologically sustainable energy sources to eventually cut back on CO_2 emissions. Countries are putting more effort into using more biofuels since they offer a way to lessen reliance on fossil fuels. Renewable fuels may contribute to the solution if they are widely available. Promising fuels for diesel engines include biodiesel and bio-alcohols [17], [18].

Ethanol (C_2H_5OH) can be produced from agricultural feedstocks. According to [19], this hydrocarbon is oxygenated, colourless, volatile, flammable, and clean burning. According to [20], ethanol can improve its cold-flow, volatility, and viscosity properties by blending it with biodiesel. According to [21], ethanol's high oxygen content can significantly lower PM emissions compared to biodiesel. Studies comparing the usage of pure biodiesel and traditional diesel to the use of ethanol blended with biodiesel have looked into how the fuel characteristics, engine performance, and emissions vary. Compared to pure biodiesel and diesel, [22] discovered that the biodiesel/ethanol blends had reduced PM and NO_x emissions but a higher heat release rate and in-cylinder pressure.

Like ethanol, n-butanol (C_4H_9OH) can be made from organic wastes containing cellulose via chemical reactions [23]. Its advantages are higher cetane number, higher heating value, lower vaporization heat, and greatly lowered hygroscopic and corrosive properties [24]. Several investigations have been done on how a diesel engine running on butanol blended with biodiesel differs from one running on traditional diesel and pure biodiesel in terms of fuel properties, performance, and exhaust features. Using varying ratios of n-butanol and biodiesel, [25] found that 15 % of the blend decreased NO emissions by 11 % and 20 % of the blend and enhanced BTE by 2.9 %.

Reference [26] evaluates the exhaust gas releases of a diesel engine using waste cooking oil biodiesel, biodiesel-10 %butanol, biodiesel-20 %butanol, and biodiesel-40 %butanol compared with pure biodiesel. The results showed that the blended fuels increased HC emission and lowered NO_x emission but slightly impacted CO emission.

Reference [27] examined the impact of biodiesel-butanol and biodiesel-ethanol mixtures on the greenhouse gas emissions and combustion parameters of diesel engines equipped with an EGR device. They discovered that the 20 % ethanol blend, 20 % butanol blend, pure biodiesel, and regular diesel resulted in higher smoke emissions. Furthermore, the NO_x emissions from the 20 % ethanol blend were lower than those from the 20 % butanol blend and biodiesel when compared to diesel. Compared to regular diesel, the blended fuels' unburned hydrocarbon and CO emissions were reduced at heavy loads but higher at low loads.

Reference [28] added 5 %butanol, 10 %butanol, 15 %butanol, and 20 %butanol into sunflower oil biodiesel to investigate the engine characteristics at full load conditions. The outcomes showed that pure biodiesel performance and emission characteristics performed better than biodiesel-butanol blends and normal diesel.

Biodiesel-ethanol blends, and biodiesel-n-butanol blends have been the subject of some research, according to the literature study. Research is still lacking in comparing the impact of biodiesel mixtures (soybean oil and waste vegetable oil) with various alcohols (ethanol and butanol) on diesel engine performance and emission characteristics. To fill in the knowledge gap, the objective of this study is to evaluate and compare the effects of diesel (D100), biodiesel mixture (BDM100), biodiesel mixture with 15 % ethanol (BMET15) and biodiesel mixture with 15 % butanol (BMBT15) of a diesel engine generator performance and emission characteristics. Performance to be investigated includes brake power, brake thermal efficiency and brake-specific fuel consumption. Emissions to be investigated include CO_2, HC, and Bosch smoke number.

2. Materials and Methods

2.1. Materials

The authors bought butanol, ethanol, methanol, potassium hydroxide (KOH), and soybean oil from Jezreel Eduscience in South Africa. The oil sample was obtained by blending waste vegetable oil, which was initially a blend of sunflower oil (90 %) and canola oil (10 %), which was gathered from the University of South Africa, Science Campus Cafeteria. The Shell gas station in South Africa is where the Diesel (D100) gasoline was bought.

Butanol and ethanol were added to the biodiesel mixture at a 15 % (v/v) blend ratio. The studied fuels had no phase separation when blended with a magnetic stirrer. The test fuels used in this experiment were pure diesel (D100) and three blends (BDM100, BMET15, and BMBT15). Various physicochemical properties of fuels were assessed to make sure they met ASTM biodiesel standards. Viscosity (ASTM D445), density (ASTM D1250), flash point (ASTM D993), and heating value (ASTM D240) of D100, BDM100, BMET15, and BMBT15 were measured using SVM 3001 Cold properties viscometer, PMA 500 Pensky-Martens flash point, and oxygen bomb calorimeter. The fuel characteristics of diesel, biodiesel mixture, ethanol blend, and butanol blend are displayed in Table 1.

TABLE 1. FUEL PROPERTIES

Properties	**D100**	**BDM100**	**BMET15**	**BMBT15**
Density (kg/m³)	0.826	0.886	0.871	0.872
Viscosity 40 °C (mm²/s)	2.66	4.411	3.255	3.259
Heating value (MJ/kg)	42.5	41.5	36.2	36.5

2.2. Methods

Free fatty acid (FFA) was first measured using a titration procedure. An accurate amount of catalyst was needed for this process to prevent inaccurate results and wasted fuel. 10 ml of isopropanol was added to one ml of waste vegetable oil, and one gram of potassium hydroxide (KOH) was dissolved in one litre of distilled water. The phenolphthalein indicator was added in three drops to form a white solution. The potassium hydroxide and distilled water mixture was then placed in a burette and titrated with the white solution until it turned pink.

The titration procedure was scientifically conducted on three separate occasions to find out the average percentage quantity. Since the amount of free fatty acid was below 2 percent, waste vegetable oil could possibly be converted straight into fatty acid ethyl ester (FAEE) through a single-step process of transformation to biodiesel without the need for pre-treatment. The outcomes were comparable to those of prior research projects that used frying oil [29]. As illustrated in Fig. 1, a 10L Pignat® biodiesel processor with a rotating blade agitation was used to perform the transesterification process. The temperature was maintained at 55 °C for 60 minutes, as was the reaction time. The alcohol-to-oil molar ratio (9:1), stirring speed (400 rpm), and catalyst concentration (1wt %) were all precisely calibrated. The catalyst, potassium hydroxide (KOH), was dissolved in the methanol (CH_3OH) by agitating. Until the 60-minute reaction time was achieved, the transesterification procedure was continued. For the duration of the evening, the resulting mixture was allowed to settle to ease the splitting of the biodiesel and glycerol. The biodiesel floated on top of the glycerol, which settled at the bottom of the separating tank. The biodiesel was cleaned with warm distilled water to get rid of impurities and glycerine. A 50 % warm distilled water was applied through the ester and gently stirred when the tank lid opened.

Five minutes afterwards, the recipient soapy water was recovered by opening the drain valve. The washing method was repeated to demonstrate that the biodiesel was catalyst-free until the bottom layer pH was comparable to pure water. Water and catalyst were removed from the biodiesel by heating it above 100 °C with the intent to enhance its overall quality. Eq. (1) was obtained by calculating the reaction yield (Y) per weight of oil after every experiment [30].

$$Y(\%) = \frac{Weight\ of\ biodiesel\ produced}{Weight\ of\ oil\ used} \times 100 \tag{1}$$

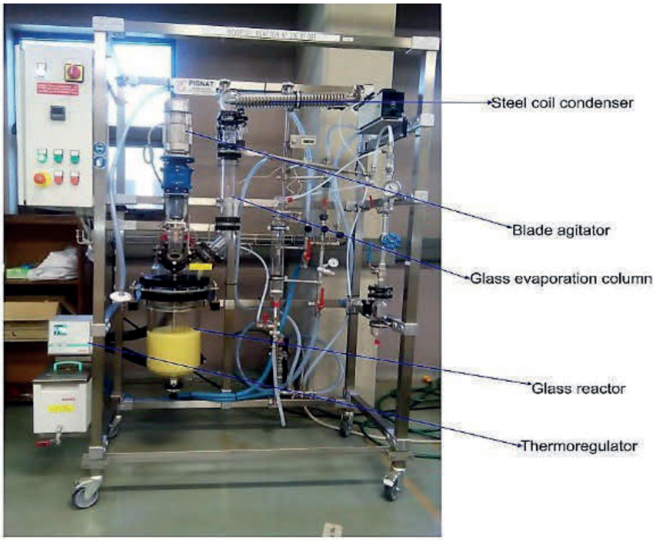

Fig. 1. Experimental Pignat biodiesel plant.

A Yanmar diesel generator fitted with an eddy current dynamometer was used for the engine testing. Figs. 2(a) and 2(b) depict the experimental system and schematic diagram of a Yanmar diesel engine. Table 2 displays detailed specifications for the engine setup. Technical parameters, including speed, torque, power, temperatures, pressures, gas flow, airflow, and emissions, were measured using the X-Tract Extreme programme, a general engineering software platform that monitors, saves, visuals, and controls. The BEA 070 type monitors the bosch smoke number emissions. The device functions on a scale ranging 0–100 %vol, with a resolution of 0.1 %. A BEA 060 type tests the hydrocarbon and carbon dioxide emissions. The levels of hydrocarbon (HC) (0–9999 ppm) and carbon dioxide (CO_2) (0–18 %vol) were observed.

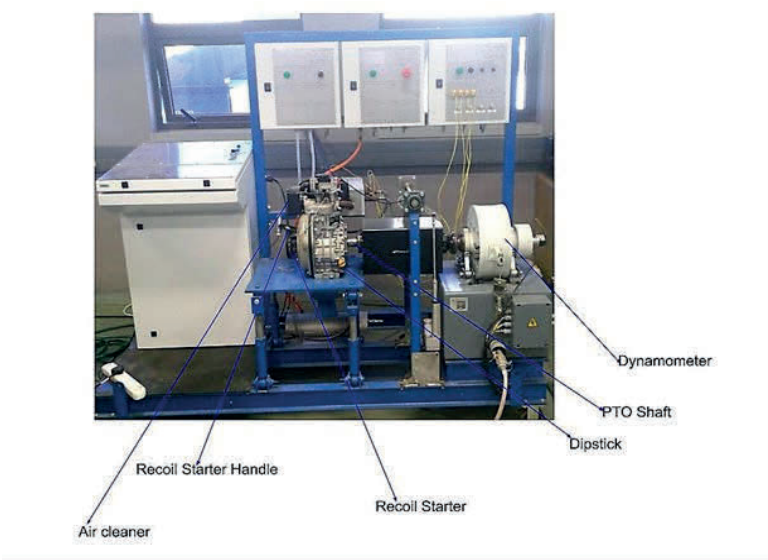

Fig. 2(a). Experimental Yanmar diesel engine facilities.

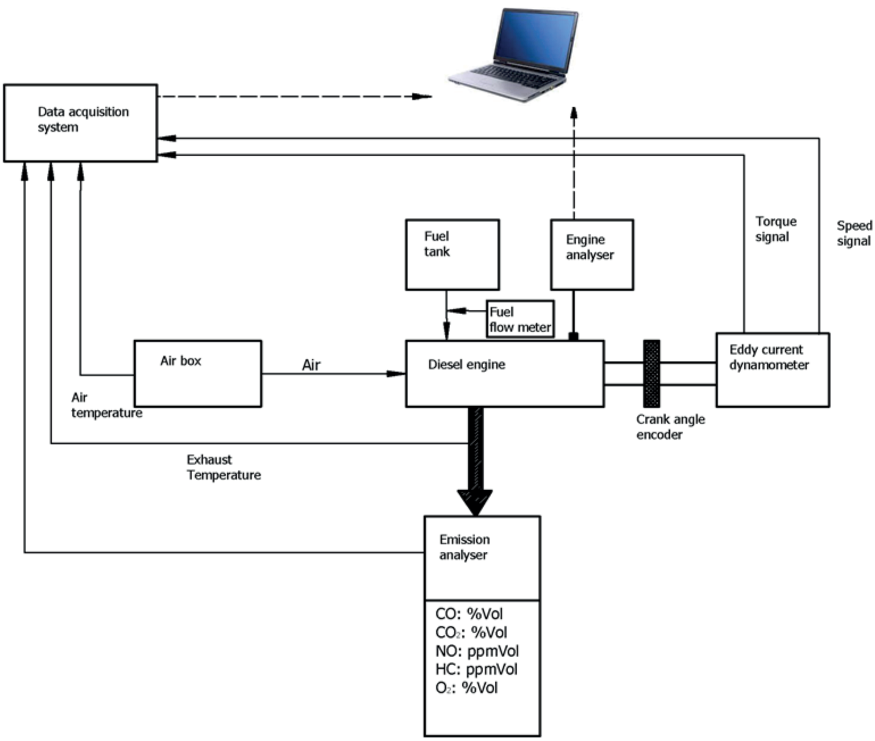

Fig. 2(b). Schematic diagram of a Yanmar diesel engine.

TABLE 2. TECHNICAL DESCRIPTIONS OF YANMAR DIESEL ENGINE

Parameters	Technical data
Model	L48N6CF1T1AA
Type	4-stroke, single-cylinder, diesel engine
Rated power	3.5 kW@3600 rpm
Compression ratio	17
Bore	57 mm
Stroke	70 mm

The engine was run for an hour to warm up before each test began. After the engine characteristics matched their requirements, operating settings were changed to test conditions. Data was stored after ten minutes of the engine running under the specified conditions. After the engine changed conditions, 10 minutes were needed to ensure it ran steadily in the new setting. The engine was operated at 1000, 1500, 2000, and 2500 rpm under full load.

2.3. Performance Parameter Assessment

The brake power (*BP*) was calculated using Eq. (2) [31] as shown below:

$$BP = \frac{2\pi NT}{60 \times 1000}\left(\text{kW}\right), \tag{2}$$

where

N speed in rpm;

T torque in N·m.

The brake-specific fuel consumption (*BSFC*) was determined from Eq. (3) [32]:

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

where

$\dot{m}_f$ mass flow rate of fuel.

The brake thermal efficiency (*BTE*) was calculated as the ratio of the brake power (*BP*) to the fuel energy input rate, as shown in Eq. (4) [33]:

$$BTE = \frac{BP \times 3600}{\dot{m}_f \times LHV}, \tag{4}$$

where

LHV lower heating value (kJ/kg) of the fuel.

2.4. Uncertainty Analysis of Engine Performance Parameters

One of the main issues the researchers deal with during measurement is the error brought on by value assessment. The term "error" refers to the measured value's variations from the actual value. The uncertainty of each measured value determines the uncertainty resulting from every variable. The relative uncertainty of the various parameters has been evaluated using standard procedures. After calculations (see Eq. 5), it was discovered that the overall uncertainty was less than the acceptable range (<5 %). The measurement range and accuracy of the speed sensor, dynamometer, HC, CO_2, and smoke emissions are shown in Table 3.

$$\% = \sqrt{(SS)^2 + (dyno)^2 + (CO_2)^2 + (HC)^2 + (smoke)^2}$$
$$\% = \sqrt{(1)^2 + (0.15)^2 + (1)^2 + (0.1)^2 + (0.1)^2} \quad (5)$$
$$\% = 1.42$$

where
SS speed sensor;
dyno dynamometer;
CO_2 carbon dioxide;
HC hydrocarbon;
Smoke smoke emission.

TABLE 3. UNCERTAINTIES OF THE PARAMETERS

Instrument	Range	Accuracy	Uncertainty
Speed sensor	0–3600 rpm	±10	±1.0
Dynamometer	0–50 kg		±0.15
CO_2	0–18 %vol	±0.01 %vol	±1.0 %
HC	0–9999 ppm	±1 ppmvol	±0.1 %
Smoke	0–100 %vol	±1 %vol	±0.1

3. RESULTS AND DISCUSSION

3.1. Brake Power

Fig. 3 clarifies the variation of brake power of the engine powered by D100, BDM100, BMET15, and BMBT15 at various engine speeds.

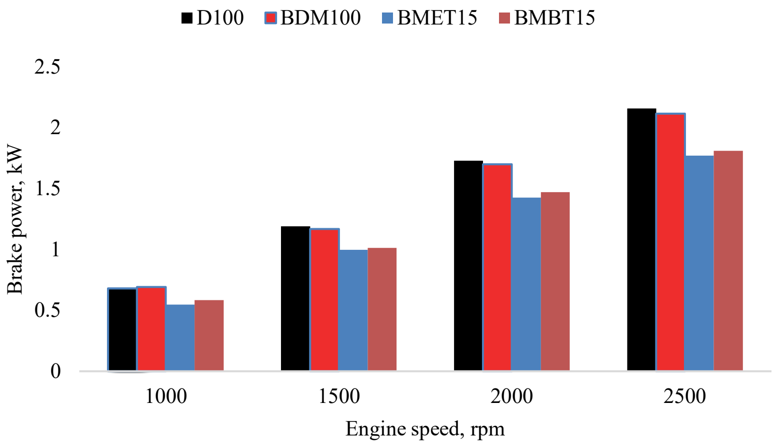

Fig. 3. Variation of brake power with engine speed.

The findings showed that, in comparison to all other green fuels, D100 achieved the highest values. A better heating value might be the cause of this maximum value. Since BMET15 has a lower heating value than all other fuel samples, it contains the lowest braking power of all evaluated fuels. The low cetane content of ethanol may also be the cause, as it influences the biodiesel mixture and lowers braking power values. The current findings, which showed that the low heating value of biodiesel with a higher percentage of ethanol blends reduced its brake power compared to conventional diesel, were consistent with the experimental findings reported by [34]. Compared to D100, the BDM100, BMET15, and BMBT15 decreased brake power by 1.94 %, 17.83 %, and 16.03 % at a maximum speed.

3.2. Brake Thermal Efficiency

The brake thermal efficiency (BTE) for D100, BDM100, BMET15, and BMBT15 has been displayed in Fig. 4 for the different engine speeds. The BMET15 brake thermal efficiency is 32.1 % at maximum speed and full load. The biodiesel mixture obtained a value of 31.4 %, the second-highest brake thermal efficiency, very close to BMET15. The BTE of the BMBT15 is 30.8 %, whereas that of the D100 is 31.2 %. These patterns correlate directly with the blend heating values in Table 1. Alcohols with a high oxygen concentration, which aid in improved combustion, provide the BMET15 with higher BTE than other blends [35].

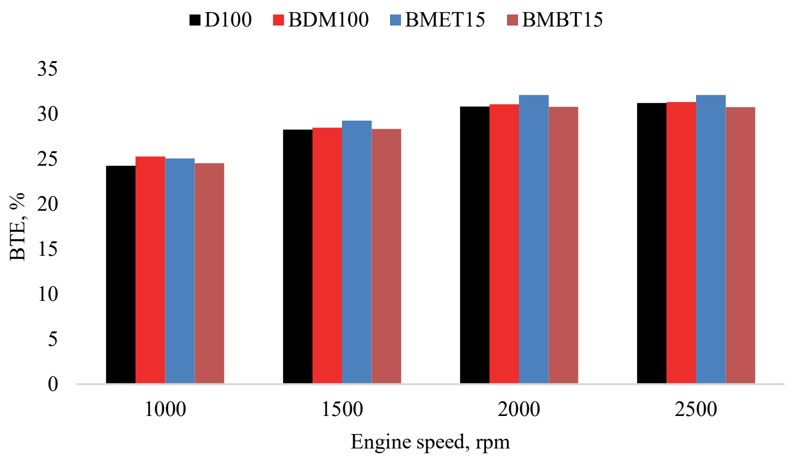

Fig. 4. Variation of brake thermal efficiency with engine speed.

3.3. Brake Specific Fuel Consumption

Fig. 5 exhibits the brake-specific fuel consumption of the D100, BDM100, BMET15, and BMBT15 at different speeds. The graph shows that, when comparing the BSFC of all the fuels, D100 has the minimum values at all engine speeds, followed by BDM100, BMET15, and BMBT15. Due to the lower heating value of biodiesel mixture-alcohol blends, all alcohol blends (BMET15 and BMBT15) achieve the maximum BSFC when compared to D100 and BDM100 [36]. The BSFC of BDM100, BMET15, and BMBT15 increased by 2.0 %, 17.8 %, and 19.1 %, respectively, at the maximum speed of 2500 rpm compared to D100. The heating value of renewable fuels directly causes this rise in BSFC.

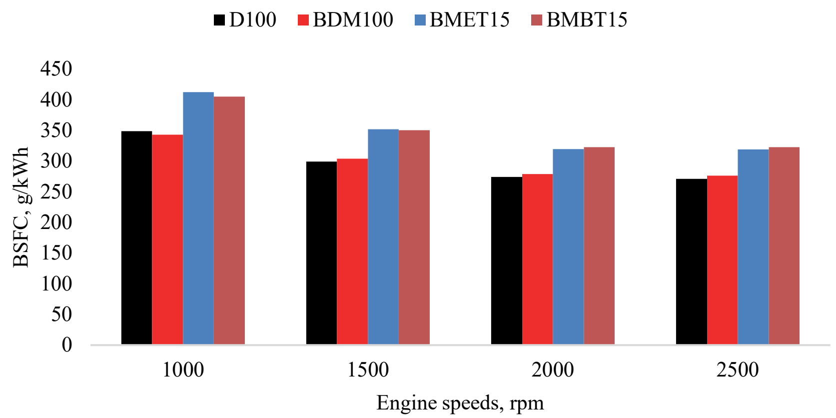

Fig. 5. Variation of brake-specific fuel consumption with engine speed.

3.4. CO_2 Emissions

As engine speed drops, the CO_2 level increases for all tested fuels, as seen in Fig. 6. The findings demonstrated that, at all engine speeds, adding butanol and ethanol to the biodiesel mixture lowers CO_2 levels compared to the pure biodiesel mixture and conventional diesel. The concentration of CO_2 in BMET15 and BMBT15 is relatively lower than that of conventional diesel, even though the fuel-bound oxygen in butanol and ethanol may oxidize hydrocarbon molecules to create H_2O and CO_2. The BMET15 produces the lowest CO_2 emissions compared to biodiesel mixtures, biodiesel mixture-butanol blend, and diesel fuel. This is because it contains less alcohol and less carbon, which reduces the generation of CO_2 [37].

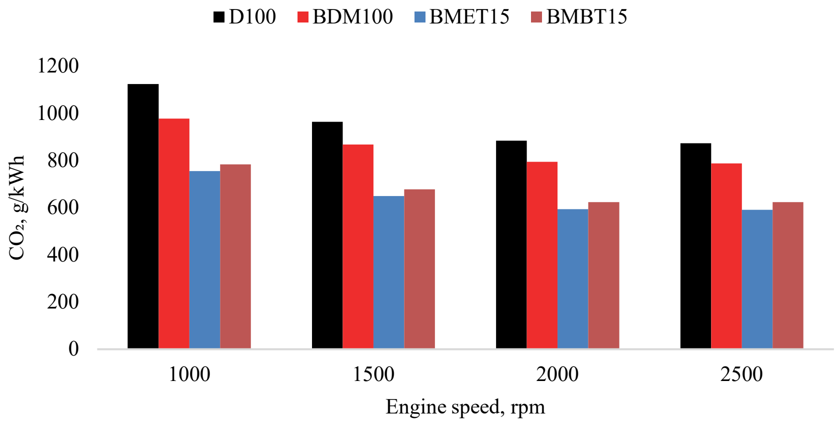

Fig. 6. Variation of carbon dioxide emissions with engine speed.

3.5. Hydrocarbon Emissions

Fig. 7 shows the variation of hydrocarbon emissions of the engine powered by D100, BDM100, BMET15, and BMBT15 at full load conditions. The results showed that the HC emissions for D100, BDM100, BMET15, and BMBT15 increase as engine speed increases. At all engine speeds, the BDM100, BMET15 and BMBT15 blends generated slightly less HC emissions compared to D100. Theoretically, because ethanol and butanol contain more oxygen, they could enhance combustion and lower HC emissions. Nevertheless, the blend cetane index dropped, and their latent vaporization heat increased with butanol and ethanol. It was, therefore, more difficult for the fuel to react with the oxygen because the blends took longer to vaporize. This resulted in a longer ignition delay and shorter combustion duration, leading to incomplete combustion and increased HC emissions [38]. Compared to D100, the BDM100 has decreased by 4.0 %, BMET15 has decreased by 26.4 %, and BMBT15 has decreased by 28.8 % at maximum speed.

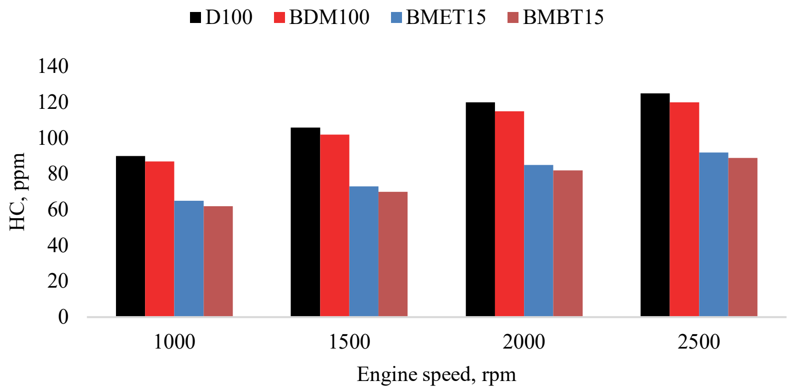

Fig. 7. Variation of hydrocarbon emissions with engine speed.

3.6. Smoke Emissions

At all engine speeds, Fig. 8 demonstrates that all alcohol blends drastically lower the Bosch smoke number emissions as compared to conventional diesel and pure biodiesel mixture.

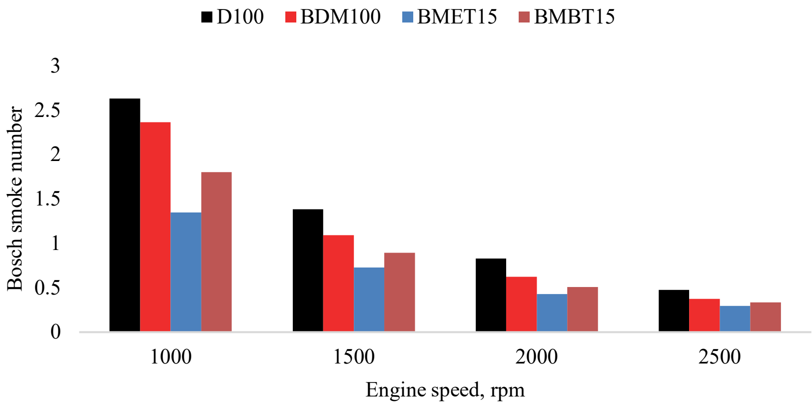

Fig. 8. Variation of smoke emissions with engine speed.

At all engine speeds, the BDM100 Bosch smoke number emissions were higher than those of the BMET15 and BMBT15. Because the alcohols in the blends are oxygenated, their Bosch smoke number emissions were lower compared to that of conventional diesel. Additionally, this decreases the amount of carbon in the blend that may be used to produce smoke [39], [40]. At a maximum speed of 2500 rpm, the BDM100 Bosch smoke number decreased by 21.1 %, the BMET15 by 38.1 %, and the BMBT15 by 29.9 % when compared to the D100.

3.7. Cost Analysis of Biodiesel Production

The cost analysis of South Africa's biodiesel production shows a possible economic environment.

Pure biodiesel price costs around R12.00 per litre

Ethanol price = R36 per litre

Butanol price = 10.20 per litre

Diesel price (50 ppm) = R18.53 per litre

BMBT15 price will be approximately:

B15% = 1.53+10.20

BMBT15 = R11.73

BMET15 price will be approximately:

E15% = 5.4+10.20

BMET15 = R15.6

4. CONCLUSIONS

In this experimental study, the effects of biodiesel mixture (BDM100), biodiesel mixture-ethanol (BMET15) and biodiesel mixture-butanol (BMBT15) blend on diesel engines were compared. The tested fuel's engine generator performance and emission characteristics were compared to each other with standard diesel fuel. The significant findings can be summarized as follows:

The BTE of the BMET15 was higher than D100, BDM100, and BMBT15 fuel.

The BSFC of D100 obtains the minimum value at maximum engine speed compared with BDM100, BMET15 and BMBT15 fuels.

The BMET15 blend emits the lowest CO_2, with CO_2 emissions of 32.4 % lower than D100 at maximum speed.

The BMBT15 blend has the lowest HC emissions compared to all other fuels.

BMBT15 blend emits the lowest smoke emissions than D100, BDM100, and BMET15 fuels at all engine speeds.

The lower percentage of butanol and ethanol blend to biodiesel mixture leads to improved aspects of engine performance and decreased exhaust gas emissions of CO_2, HC, and Bosch smoke number while exceeding a 15 % alcohol blend may lead to a variation of negative effects that exceed the possible benefits.

In light of its affordability, reduced greenhouse gas emissions from diesel engines, competition for land from food crops versus energy sources, feedstock availability, and sustainability, waste vegetable oil as a biodiesel production is probably the most viable choice. Using biodiesel from waste vegetable oil will benefit the economy, the environment, and investment because it will save revenue. This is especially important because South Africa's demand for liquid fuel is still being met by imports, which drives up fuel prices. Using waste vegetable oil to produce biodiesel may boost the economy and reduce the price of importing fossil fuels.

The negative effects of biofuels on engine performance can lead to power and torque reduction and high specific fuel consumption due to their lower heating value compared to standard diesel fuel.

For further research, long-term engine testing is needed to assess the durability and reliability of biodiesel mixture-ethanol blend and biodiesel mixture-butanol blend. The decrease of brake-specific fuel consumption for biodiesel mixture, while ethanol and butanol blend increases, needs further investigation. The impact of alcohol blends on BSFC is less clear and needs further investigation.

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