DOI: https://doi.org/10.54966/jreen.v27i1.1152 - *Journal of Renewable Energies 27 (2024) 47 – 66*

Journal of Renewable Energies
Revue des Energies Renouvelables
journal home page: https://revue.cder.dz/index.php/rer

Research paper

Performance, combustion, and emission features of a diesel engine powered by biodiesel mixture and butanol blends

Shumani Ramuhaheli [a,*], **Christopher Enweremadu** [a]

[a] *University of South Africa, Department of Mechanical Engineering, Science Campus, Florida, Johannesburg, South Africa*

ARTICLE INFO

Article history:
Received December 17, 2023
Accepted May 15, 2024

Keywords:
Butanol,
Biodiesel Mixture,
Performance,
Combustion,
Emission Characteristics.

ABSTRACT

The search for permanent fossil fuel substitutes has become critical due to the declining supply of fossil fuels and the toxic pollution emitted by diesel engines. In this study, diesel engine characteristics have been investigated numerically and experimentally using diesel, biodiesel mixture from waste vegetable oil and soybean oil (BM100), and butanol blends (5%, 10%, and 15%). The experimental work was conducted on the single-cylinder diesel engine generator at different speeds (1000, 1500, 2000, and 2500 rpm) and full load conditions. A commercial Diesel-RK software was used to perform the numerical aspects of the diesel engine. The different percentages of butanol blends were added to biodiesel mixture to form biodiesel mixture-butanol blends. It was discovered that there was good agreement between the experimental and numerical results. The cylinder pressure, heat release rate, brake power, brake-specific fuel consumption, brake thermal efficiency, nitrogen oxide, carbon dioxide, and particulate matter (PM) emissions were all predicted using the numerical technique. Results showed a decrease in carbon dioxide, particulate matter, and brake power. When compared to regular diesel fuel, at maximum speed, there was a decrease in brake-specific fuel consumption and an increase in nitrogen oxide emissions.

1. INTRODUCTION

Diesel, gasoline, coal, and other non-sustainable fossil fuels are widely applied in the automotive, power generation, agricultural, and industrial sectors. Apart from their continuous depletion, these energy resources are linked to certain negative environmental effects resulting from toxic emissions, not to mention the growing population and rising energy demands. Oil surpassed all other energy sources as the primary energy source globally in 1950. In addition to many other applications, it produces plastics,

---

[*] *Corresponding author, E-mail address: ramuhs@unisa.ac.za*
Tel: +27 11471 2078

ISSN: 1112-2242 / EISSN: 2716-8247

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License. Based on a work at http://revue.cder.dz.

heat, light, and transportation. The average amount of barrels consumed each day between 2017 and 2023 was 100 million, and as this figure is rising quickly, the reserves are continually depleting (Pitchaiah et al., 2023). This motivates scientists to search for and investigate new, limitless alternative energy sources. Decarbonization, which aims to eliminate or minimize carbon dioxide emissions from the environment, is also a major global concern that can be resolved by switching to the use of low-carbon energy sources.

Researchers have suggested that biodiesel is the most promising alternative fuel in this context due to its less harmful, renewable, lower carbon footprint, and is more sustainable than conventional fuel (Semwal et al., 2011). Biodiesel is a kind of liquid fuel that is mainly produced from plants, including vegetable and animal fats, waste vegetable oils, microbial oils, algae oils, and animal fats (Swarna et al., 2022; Mahmudul et al., 2017). It usually has a higher viscosity, higher cetane number, and higher level of oxygen than normal diesel fuel, which produces a shorter ignition delay period.

The direct use of biodiesel in a diesel engine is inappropriate due to some negative effects including higher density, higher viscosity, low temperature, and lower volatility qualities (Datta & Mandal, 2016; Datta & Mandal, 2017). Furthermore, it affects the engine combustion quality and increases emissions such as smoke, carbon dioxide, carbon monoxide, and particulate matter (Karthikeyan, 2019; Soudagar et al., 2021). However, many researchers suggest the blending of diesel and biodiesel using different proportions. Blending of fuels improves their physical and chemical properties, which increases their performance characteristics and operating cycles.

Recent research suggests that ternary blends, such as diesel-biodiesel-alcohol could improve their low volatility, high viscosity, and low-temperature behavior. Because they are mostly made from biomass, alcohols such as butanol, heptanol, and methanol are sustainable fuels. Alcohol has a higher oxygen content, therefore when engines are running at high loads, the hydroxyl (OH) group in alcohol produces less exhaust gas. Engine torque decreases due to an increase in brake-specific fuel consumption (Lapuerta et al., 2018; Nour et al., 2019a).

Since higher alcohols have closer physicochemical properties to standard diesel than lower alcohols, several scientists have investigated the use of higher alcohols as an addition to biodiesel-diesel or biodiesel to produce binary blends or ternary blends, which can replace standard diesel. High alcohols with long-chain carbon molecules in their molecular structure have shown exceptional chemical and physical properties that make them the perfect fuel for diesel engines (Kumar & Saravanan, 2016; Babu & Murthy, 2017).

Researchers have examined the impact of ternary blends of fuels including diesel-biodiesel-alcohol blends and biodiesel-alcohol blends on engine performance, combustion parameters, and exhaust gases using a range of feedstocks and higher alcohol blends (Prbakaran & Viswanathan, 2018; Wei et al., (2018); Ramuhaheli et al., (2022)).

Devarajan et al. (2019) tested the engine characteristics of punnai oil biodiesel with the addition of butanol as an enhancer at 5% and 10%. The results indicated that the BTE has been decreased with the addition of butanol. All of the punnai biodiesel blended with butanol had higher BSFC compared with regular diesel. The addition of butanol to biodiesel significantly decreased emissions of CO, NO_x, and PM, while its HC emissions increased compared to regular diesel. Every blend of biodiesel had a peak pressure during the combustion process compared to regular diesel. When butanol was blended with biodiesel, the heat release rate (HRR) showed a decrease in all butanol blends due to high fuel consumption.

Singh et al. (2020) present their findings on a combustion study using a diesel engine powered by blends of butanol, diesel, and eucalyptus oil biodiesel. Both two-component mixtures containing biodiesel in the proportion of 20% and 80% diesel and ternary blends including 20% biodiesel, 75% diesel fuel, and 5% butanol were evaluated. The results show that the percentage of butanol reduces CO emissions by 10%, total hydrocarbons (THC) emissions by 40%, and NO_x emissions by about 20%, while simultaneously increasing engine power and BSFC. It was concluded that a combination of butanol, diesel, and biodiesel may serve as an alternative to diesel.

Huang et al. (2020) studied the effects of using biodiesel and butanol blends in a diesel engine for agriculture on performance parameters, combustion, and exhaust gases. The BBu10 (90%biodiesel10%butanol), BBu20 (80%biodiesel20%butanol), and BBu30 (70% biodiesel30%butanol) were the mixture of biodiesel and butanol whose combustion was examined. However, the blends had 10%, 20%, and 30% by weight of butanol. When butanol was added to biodiesel, it was discovered that the higher cylinder pressure and temperature were slightly reduced, but the maximum pressure rate and heat release rate increased. Moreover, there was a decrease in combustion and a delay in fuel ignition. BBu20 exhibited igniting qualities similar to those of diesel fuel. The BBu30 of CO, NO_x, and soot emissions decreased by 17.6%, 34.1%, and 15%, respectively, but its average gains in BTE and BSFC were 2.7% and 14.9%, respectively.

The impacts of butanol-biodiesel-diesel fuel (BBD) on engine characteristics were investigated experimentally by Divakar Shetty et al. (2017). The standard diesel, biodiesel, and butanol were blended in different ratios to produce blends with various fuel properties including density, viscosity, flash point, and heating value. The engine test was conducted with varying loads and speeds. The fuel properties data clearly show that the fuel density, viscosity, and flash point decrease with increasing butanol content in BBD blends. Furthermore, it was observed that the exhaust gas temperature and brake thermal efficiency increased with the amount of butanol in the BBD mixture. On the other hand, the brake-specific fuel consumption decreases as the butanol content of the BBD blends increases. An increase in butanol content in BBD increases CO, HC, and NO_x emissions.

The characteristics of a biodiesel and butanol mixture's combustion procedure in a diesel engine at different loads were presented by Xiao et al. (2020). They discovered that butanol enhances fuel atomization and evaporation, which benefits the combustion process directly. The amount of butanol increased, which led to a shorter combustion period and an increase in ignition delay. They discovered lower CO emissions while THC emissions increase over the entire load range. The NO_x emissions sharply increased. Another finding indicated that an increase in the proportion of butanol gives an increase in PM emission in the range<10 μm and a significant decrease in the emission of larger particles.

Imtenan et al. (2015) reported on the effects of 10% butanol blends in a combination containing Jatropha biodiesel on the process of combustion in a compression ignition engine. It was found that butanol affected the ignition delay and affected the rate at which combustion started. The mixture altered cetane number causes the fuel containing butanol to produce higher maximum pressure values. The specific fuel consumption increased as the calorific value of butanol dropped. A decrease in both CO and soot emissions was observed. Additionally, the engine's THC gases were much lower than the standard diesel fuel.

Research by Zhang & Balasubramanian (2014) and Zhang & Balasubramanian (2016) indicates that adding butanol to diesel-palm biodiesel (B20) at a rate of up to 15% increased engine brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC) of the diesel engine.

Nour et al. (2019a) used a diesel engine to evaluate the engine parameters of mixtures containing higher percentages of alcohol including butanol, octanol, and heptanol at 10 percent and 20 percent proportions. The findings revealed that BTE and BSFC climbed for all alcohol/diesel mixtures. Higher alcohol/diesel blends demonstrate longer ignition delay and faster-premixed combustion, which increases the total net heat release. Furthermore, CO and HC pollution increased whereas smoke opacity and NO_x releases declined for butanol, octanol, heptanol, and diesel blends.

The compression ignition (CI) engine operating process can be simulated using the Diesel-RK thermodynamic model, which can also be used to describe exhaust gases, temperature and pressure distribution, and ignition delay. This makes it a less expensive, time-consuming, and computationally exhaustive optimization tool. This software program, which is available for free, is useful for simulating CI engines and optimizing several engine parameters simultaneously for both single and multi-cylinder applications. However, commercially available computational fluid dynamics (CFD) software has a higher capital expenditure and takes longer to solve issues. Numerous scientists have conducted various numerical and experimental investigations of internal combustion diesel engines using different biofuels. In this respect, the Diesel RK model has proven to be an efficient instrument (Dawody & Bhatti, 2013; Kuleshov et al., 2010; Datta & Mandal, 2017).

According to the literature review, some research has been done on diesel-biodiesel-butanol blends or biodiesel-butanol blends. However, the literature search did not return much work carried out on biodiesel mixtures (waste vegetable oil and soybean oil) and butanol blends to evaluate their performance, combustion, and emission characteristics at different speeds. Hence, an alcohol type (butanol) was selected to carry out the numerical analysis. The objective of this study was to contribute to the information available by conducting a numerical assessment of the impacts of butanol blends on engine parameters using a biodiesel mixture blended with various percentages (5%, 10%, and 15% v/v) of butanol, with conventional diesel serving as the reference. Diesel-RK, a suggested numerical solver, was used to validate the results from the experiments.

2. OVERVIEW OF BIODIESEL PRODUCTION IN SOUTH AFRICA AND AFRICA

The use of biofuel in South Africa began in the 1920s when gasoline and sugar ethanol blended (Blanchard et al., 2011). Blending was abandoned at the start of the 1960s since it was no longer cost-effective due to the lower cost of importing fossil fuels. Politicians and the general public are once again becoming interested in biofuels due to their capability to provide energy and stability for the economy. In response to the growing awareness of the need for biofuels in the nation, the South African government launched the Biofuels Industrial Strategy in 2007 (Pradhan & Mbohwa, 2014).

Biofuel production in South Africa is still in its infancy, despite numerous policy declarations and plans over the years, and the nation has very few small-scale biofuel plants (Avinash et al., 2014). There were already 200 or so small plants that produce biodiesel; these plants primarily use waste vegetable oil (WVO) as a feedstock, which doesn't compete with food or arable land. Batch reactors are less expensive to acquire, have simpler designs, and are easier to operate than continuous reactors, the production rate of these plants is relatively modest (Mbohwa & Mudiwakure, 2013). The huge volume of used cooking oil produced in Algeria offers both benefits and challenges. Although there are health and environmental risks associated with this waste, it also offers a useful supply of raw materials for different purposes, including the production of bio-based products and biodiesel (Bessah et al., 2023). Shortly, SN CITEC (Dagris Group) intends to construct a cottonseed-based plant in Burkina Faso with a 10,000-ton yearly capacity for production (Rendleman & Shapouri, 2007). With an estimated 10,000 km of Jatropha hedges and an annual growth rate of 2,000 km, Mali can produce 1,700,000 liters of oil. In the regions of Mali where they are most common, these hedges often range from two to fifteen kilometers per town, with the potential to reach forty kilometers per community. The goal established by the Mozambican government was to blend 5% biodiesel into diesel. According to the objective established, the state oil company Petromoc plans to manufacture 185 million liters of biodiesel, which will be more than sufficient to meet the needs of the Mozambican market (De Castro, 2007). The production of Jatropha oil as a source of biodiesel is of special importance to those in the business community in Togo. Based on initial analyses using projections of costs for multiple production factors, biodiesel may be able to compete with traditional diesel at 5% cheaper. However, the competitive production of Jatropha seeds continues to be a subject of concern (Rendleman & Shapouri, 2007).

3. MATERIALS AND PROCEDURE

3.1 Materials

Potassium hydroxide (KOH), butanol, methanol, and soybean vegetable oil were purchased from Jezreel Eduscience, South Africa. Waste vegetable oil, originally a mixture of sunflower oil (90%) and canola oil (10%), was collected from the science campus cafeteria, University of South Africa, South Africa, and blended to obtain the oil sample. The diesel (D100) fuel was purchased from a Shell gas station, in South Africa. The waste vegetable oil was filtered by filter funnel 155 mm plastic funnel to remove solid impurities. To get rid of the water, the oil was heated at 100°C for 30 minutes (Danane et al., 2022).

3.2 Biodiesel production and experimental procedure

The transesterification process was conducted in a 10 L Pignat® biodiesel reactor fitted with a blade agitator as shown in Fig 1. For 60 minutes, both the reaction time and temperature were maintained at 55°C. The ideal ratio of alcohol to oil molar ratio (9:1), stirring speed (400 rpm), and catalyst concentration (1wt%) were used. The catalyst potassium hydroxide (KOH) was dissolved into methanol (CH_3OH) by stirring. Six liters of oil were introduced into the biodiesel glass reactor tank. After the appropriate temperature was reached, the prepared solutions of 55.8 grams of potassium hydroxide (KOH) catalyst and 2.2 liters of methanol (CH_3OH) were added and stirred into biodiesel. The transesterification process was continued until the 60-minute reaction time was achieved. To facilitate the separation of biodiesel and glycerol, the mixture was allowed to settle for a whole night. The biodiesel floated on the top layer in the separation tank, while the glycerol settled at the bottom (Fig. 2). After that, contaminations were removed from the biodiesel by washing it with 50% more warm distilled water. Up till the bottom layer pH was comparable to that of pure water, indicating that the biodiesel was catalyst-free, and the washing process was repeated. To improve the quality of the biodiesel, water, and catalyst were eliminated by heating it over 100°C.

Three samples of ternary blends, with butanol oxygenated additive (5%, 10%, and 15%) and biodiesel mixture (waste vegetable biodiesel and soybean biodiesel) were formed and based on the percentage volume to ensure the similarity of the blends. The ASTM standards were used to evaluate the properties values of these blends such as biodiesel mixture (BM100) (WVB 50%, SB 50%, and butanol 0%), biodiesel mixture and butanol blends (BMBT5) (WVB 80%, SB 15%, and butanol 5%), BMBT10 (WVB 70%, SB 20%, and butanol 10%), and BMBT15 (WVB 60%, SB 25%, and butanol 15%). Butanol was added to the biodiesel mixture (waste vegetable oil and soybean oil) to decrease the density and viscosity, bringing these crucial characteristics closer to those of diesel fuel. The characteristics of standard diesel, BM100, BMBT5, BMBT10, and BMBT15 are displayed in Table 1.

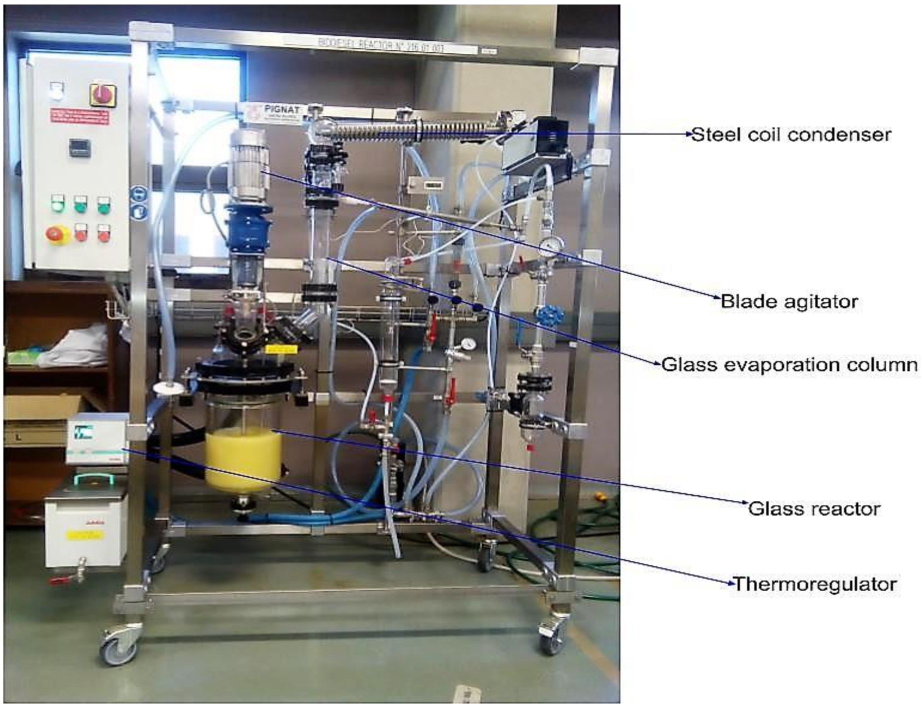

Fig 1. Experimental Pignat® biodiesel plant

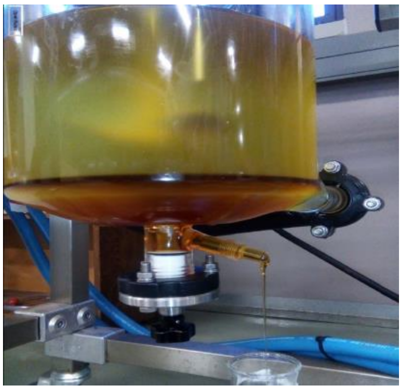

Fig 2. Biodiesel and glycerol separation

3.3 Fuel properties

Different physicochemical properties of pure biodiesel mixture and biodiesel mixture-butanol blends were measured to ensure suitability with ASTM biodiesel standards. Viscosity (ASTM D445), density (ASTM D1250), flash point (ASTM D993), and Heating value (ASTM D240) of biodiesel mixture and butanol blends were measured using an SVM 3001 Cold Properties Viscometer, Rudolph's DDM2910 digital density meter, PMA 500 Pensky-Martens flash point, and oxygen bomb calorimeter (IKA C1), respectively.

Table 1. Fuel properties.

Properties	D100	BM100	BMBT5	BMBT10	BMBT15
Density (kg/m^3)	0.8263	0.886	0.882	0.878	0.872
Viscosity (mm^2/s)	2.66	4.411	4.068	3.633	3.259
Heating value (MJ/kg)	42.5	41.5	37.3	37	36.5

3.4 Engine setup and operating conditions

The engine parameters, and exhaust gas emissions were assessed using single cylinder, Yanmar diesel engine generator. The schematic diagram of a diesel engine is indicated in Fig. (3), and their descriptions are listed in Table 2. The highest speed and power output of the diesel engine were 2500 rpm and 3.5 kW. The diesel engine, fuel, and airflow metering device, eddy current dynamometer, and data collection system were connected to the X-Tract extreme software data analyzer. The engine speed and load were managed by an eddy current dynamometer. A Promass 83 Endress and Hauser fuel meter is used to measure the fuel gauge. The pressure sensor and crank angle encoder were applied to measure the cylinder pressure and crank angle. The instrument used for testing emissions was the Bosch exhaust analyzer. An exhaust gas analyzer model BEA060 measures NO_x, PM, and CO_2 emissions.

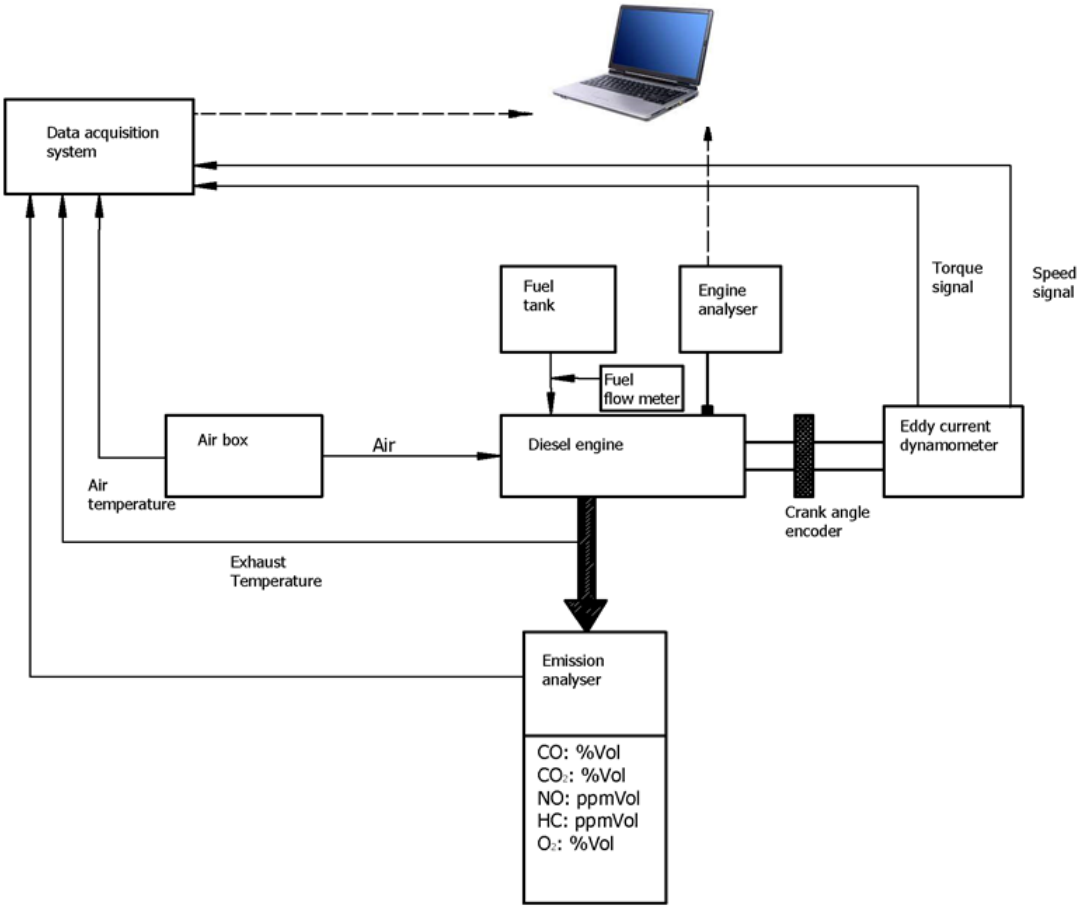

Fig 3. Layout of the experimental setup.

Table 2. Technical descriptions of the engine

Specifications	Description
Type	4-stroke, air-cooled, Yanmar Diesel engine generator
No. of cylinders	1
Rated Power	3.5 kW@3600 rpm
Injection system	Direct injection
Compression Ratio	17.1

3.5 Uncertainty analysis

To evaluate experimental error, uncertainty analysis is necessary. The most common reasons for errors in each specific experiment involve analyzing findings, surrounding factors, and measuring apparatus. The portion of uncertainty for each parameter is presented in Table 3. By applying the square root method, the total proportion uncertainty in the experiment may be predicted, and the outcome is as follows:

$$\%=\sqrt{(Dyna)^2+(load)^2+(pressor\ sensor)^2+(CA\ encoder)^2+(CO_2)^2+(NO)^2} \tag{1}$$

$$\%=\sqrt{(0.15)^2+(0.2)^2+(0.5)^2+(0.2)^2+(1)^2+(0.5)^2}$$

$$\%=1.3$$

Table 3. Uncertainties of the parameters

No.	Instrument	Type	Range	Accuracy	Uncertainty
1	Dynamometer	Load cell	0-50 kg		±0.15
2	Crank angle encoder		0-3600 ppr	±1 ^{0}	±0.2
3	Load indicator		0-20 kg	±0.1 kg	±0.2
4	Pressure sensor	Piezoelectric	0-100 bar	±1 bar	±0.5
5	CO_2		0-18 %vol	± 0.01%vol	±1.0
6	NO		0-5000 ppm	±1 ppm vol	±0.5

3.6 Numerical procedure

Diesel-RK computer simulation software has developed the mathematical formula that forms the foundation for a computational code and multizone combustion model (Kuleshov, 2006; Al-Dawody & Bhatti, 2013). To analyze the internal combustion engine performance, released gases, and combustion characteristics, Diesel-RK software was developed for energy conservation. Fuel characteristics were used by the Diesel-RK computer simulation model to analyze mixture formation and combustion characteristics. With the use of standard diesel fuel, biodiesel mixture (waste vegetable oil and soybean oil), and butanol blend qualities, a computational model of a Yanmar generator diesel engine was loaded into the Diesel-RK simulation program.

The elementary equation of the state clarifies that the net sum of rate displacement work, rate of heat transfer, and enthalpy flux are derived from the governing equation. The governing equation on the conservation of energy can be written as follows (Kuleshov, 2005):

$$\frac{d}{dt}(mu)=-p\frac{dv}{dt}+\frac{dQ_{ht}}{dt}+\sum_j \dot{m}_j\,h_j \tag{2}$$

Where $\frac{d}{dt}(mu)$ is the change of energy in the structure, $-p\frac{dv}{dt}$ is the net sum of rate displacement work, $\frac{dQ_{ht}}{dt}$ is the rate of heat transfer, and $\sum_j \dot{m}_j\,h_j$ is enthalpy flux.

There are four primary stages to the combustion process, and each stage has specific physical properties. (Kuleshov, 2005) provides these stages:

Using a modified version of Tolstov's equation (Al-Dawody & Bhatti, 2013), the ignition delay is given by:

$$\tau=3.8X10^{-6}(1-1.6X10^{-4}.\mathrm{n})\sqrt{\frac{\mathrm{T}}{\mathrm{P}}}\exp\left(\frac{\mathrm{E_a}}{8.312\mathrm{T}}-\frac{70}{\mathrm{CN}+25}\right) \tag{3}$$

Where n is the engine speed (rpm), P is the engine pressure (bar), T is the engine temperature (K), Ea is the activation energy (kJ/kmol), CN is the cetane number, and X is the fuel burned ration during ignition delay.

The following is the expression for the heat release rate premixed combustion period:

$$\frac{dx}{d\tau} = \Phi_0 X\left(A_0\left({m_f}/{V_i}\right)X(\sigma_{ud} - X_0)\right) + \Phi_1 X\left(\frac{d\sigma_u}{d\tau}\right) \quad (4)$$

Where m_f is mass per cycle, V_i is cylinder volume of injection period, $\sigma_{ud,}$ and σ_u are fuel percentages evaporations ignition delay.

The heat release rate during the controlled mixing combustion stage time is expressed as follows:

$$\frac{dx}{d\tau} = \Phi_1 X\left(\frac{d\sigma_u}{d\tau}\right) + \Phi_2 X\left(A_2\left(\frac{m_f}{V_c}\right)X(\sigma_u - X)X(\alpha - X)\right) \quad (5)$$

Where V_c is a notation explanation in-cylinder volume of the top dead center (TDC).

The late burning stage period period of heat release rate has been given as:

$$\frac{dx}{d\tau} = \Phi_3 A_3 K_T(1 - X)(\xi_b\alpha - X) \quad (6)$$

Where ξ_b stands for air efficiency and α represents the air-fuel equivalency ratio. The four-stage period equations are presented as $\Phi_0 = \Phi_1 = \Phi_2 = \Phi_3$, and the parameter Φ_0 in the heat release rate model equations indicate how completely the fuel vapor combusts in the zones, and the four-stage period equations are given as $\Phi_0 = \Phi_1 = \Phi_2 = \Phi_3$. While A_3 is found in equation (6), A_0, A_1, and A_2 can be understood as the empirical portion that relies on engine speed and swirl strength.

Woschni's equation (Woschni, 1967) is used to evaluate identical heat transfer coefficients for different areas while taking into account the diesel engine cylinder of the heat transfer.

$$h_c = 3.26 \times B^{-0.2} \times p^{0.8} \times {v_g}^{0.8} \times T^{-0.53} \quad (7)$$

Where B is used for bore length (m) and V_g represents the velocity of the gas (m/s).

By applying energy conservation, the heat release rate (HRR) was calculated using the information gathered from the in-cylinder pressure measurements. According to Heywood (2018), the HRR was calculated using Equation (8) in the following manner to account for energy conservation:

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dp}{d\theta} \quad (8)$$

The heat release rate is represented by Q_n, the cylinder pressure is represented by p, the specific heat ratio by γ, the cylinder volume by V, the crank angle by θ, and the volume proportional to the crank angle is represented by $\frac{dV}{d\theta}$. For heat release analysis, the specific heat ratio with the value of ($\gamma = cp/cv$) is 1.35.

The following formula was used to determine the in-cylinder volume (V) corresponding to any crank angle point:

$$V = V_C\left\{1 + \frac{1}{2}(r - 1)\ \left[R + 1 - \cos\theta - (R^2 - \sin^2\theta)^{\frac{1}{2}}\right]\right\} \quad (9)$$

Where r stands for engine compression ratio, V_c for engine clearance volume (m^3), and R for connecting rod length ratio to crank radius.

3.7 Model validation

The engine description mentioned in Table 2 was used to develop the Diesel-RK model, which was then validated against experimental data. The experimental data for cylinder pressure and heat release rate were compared with the modeling results for diesel fuel at full load conditions and a maximum speed of 2500 rpm. It is necessary to compare the Diesel-RK model and experimental data for engine design in various methods to achieve reliable simulation results and to calibrate models when differences are found. The highest percentage variation of 1.85% and 8.25% at full load conditions were within the allowed ranges for the peak values of the selected variables' percentage fluctuation. It was discovered that the percentage change in the peak values of the chosen parameters did not exceed the approved limitations. Figs. (4) and (5) display the verified results for the cylinder pressure and heat release rate, respectively.

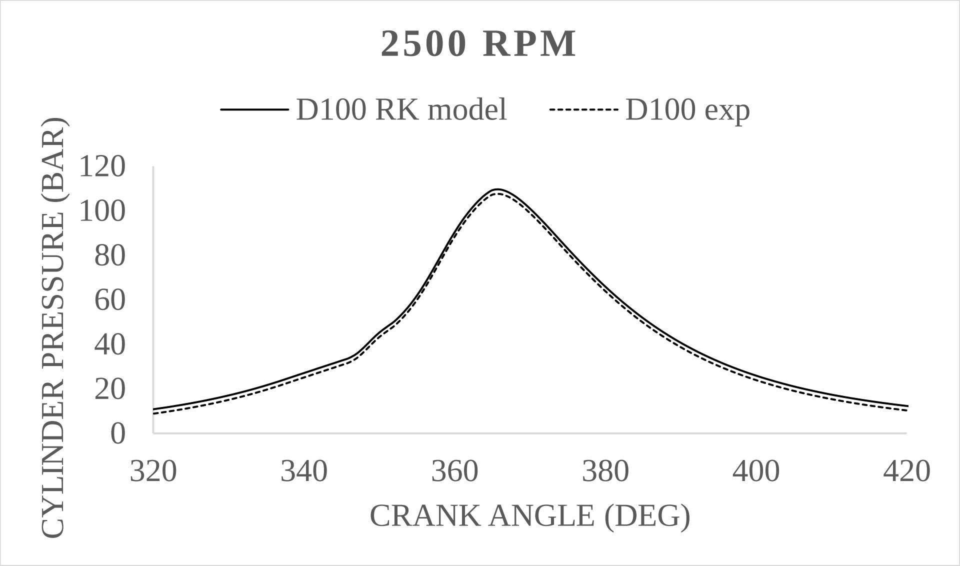

Fig 4. Cylinder pressure vs crank angle.

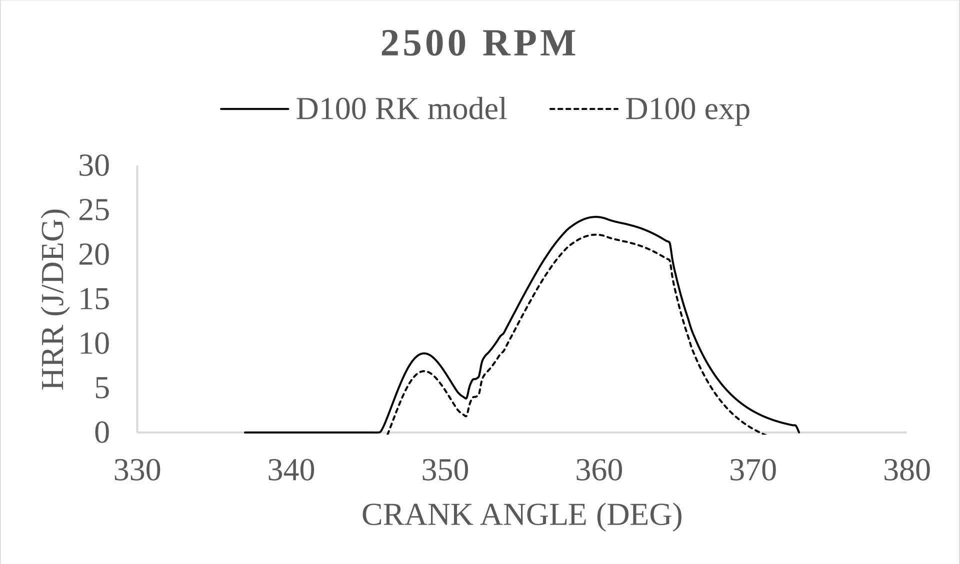

Fig 5. Heat release rate vs crank angle.

4. RESULTS AND DISCUSSIONS

4.1 Brake power

Figure (6) illustrates the various effects of standard diesel, biodiesel mixture and butanol blends brake power throughout a range of engine speeds. Among all the fuels evaluated at all engine speeds, the BP of BMBT15 has the lowest value due to its low heating value. Nonetheless, while the diesel engine operates at its maximum speed, D100 offers the maximum value when compared to all other green fuels due to its higher heating value. For the D100, BM100, BMBT5, BMBT10, and BMBT15, the BP at maximum speed is 2.16 kW, 2.12 kW, 1.88 kW, 1.86 kW, and 1.84 kW. The findings of the test show that a diesel engine brake power increases with engine speed (Al-Dawody et al., 2022).

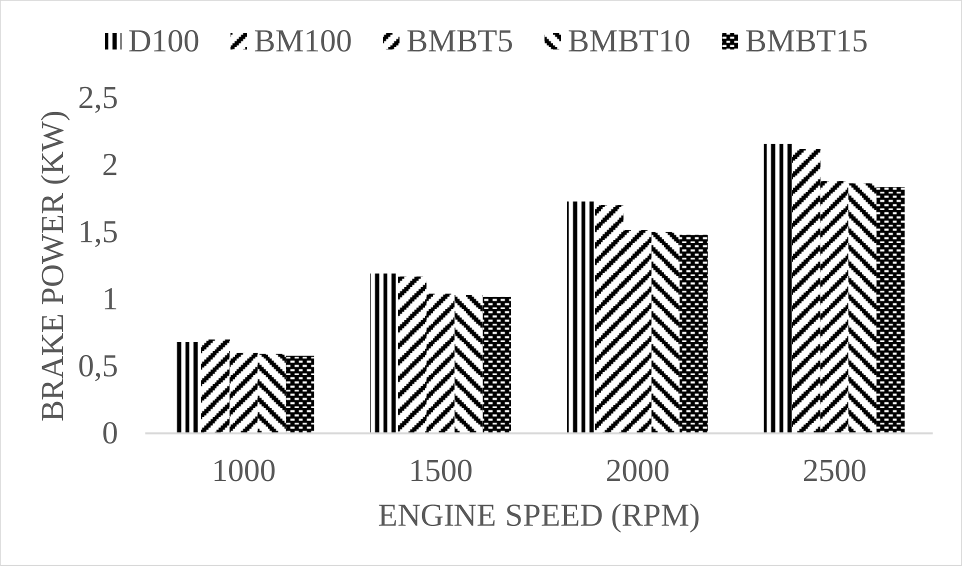

Fig 6. Brake power based on engine speed.

4.2 Brake specific fuel consumption

Figure (7) shows the change in BSFC for diesel engines running at different speeds and with different prepared fuel mixtures. The BSFC specifies the quantity of fuel the engine unit needs to generate the required power. According to Ahmad & Saini (2022), the BSFC is significantly impacted by the heating value, density, and viscosity. When engine speed rises, the BSFC of the test fuels decreases and shows consistent trends for each test fuel. For D100, BM100, BMBT5, BMBT10, and BMBT15, the BSFC at maximum speed are 271 g/kWh, 276.2 g/kWh, 310.8 g/kWh, 313.8 g/kWh, and 318.8 g/kWh. In comparison to BM100, standard diesel obtains the lowest BSFC outcomes. Compared to clean diesel fuel, BM100 obtains the minimum BSFC due to higher heating value. Among all test blends, BMBT15 and BM100 had the highest and lowest BSFC values, respectively, while diesel contains the lowest amount of BSFC because it has the highest heating value.

4.3 Brake thermal efficiency

Figure (8) illustrates the BTE for D100, BM100, BMBT5, BMBT10, and BMBT15 at different speeds. According to findings, BTE demonstrates similar tendencies for each of the tested fuels and declines as butanol percentage increases but increases with engine speed. Diesel and BM100 obtain the highest BTE compared to all butanol blends due to their maximum heating values, whereas the BTE of BM100 is the highest of all green fuels due to heating value. With a maximum speed of 2500 rpm, the highest BTE values for D100, BM100, BMBT5, BMBT10, and BMBT15 are 31.3%, 31.4%, 31.2%, 31.3%, and 31.2%, respectively. (Ahmad & Saini, 2022) have reported comparable results.

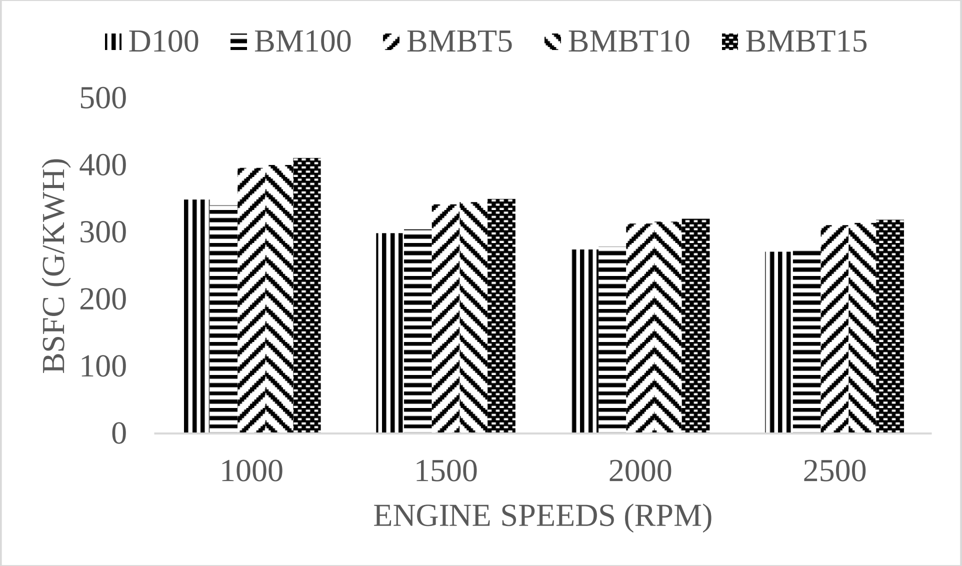

Fig 7. Brake-specific fuel consumption based on engine speed.

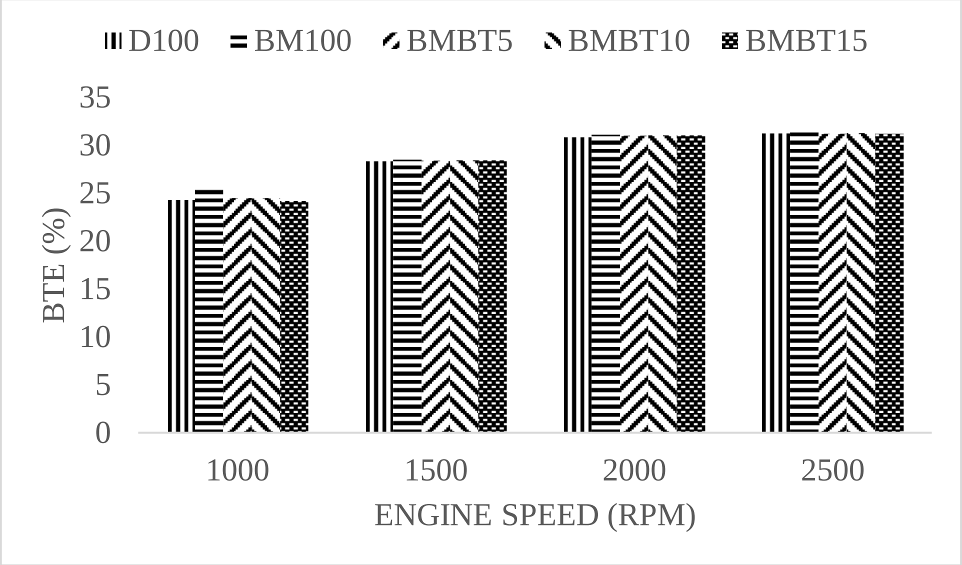

Fig 8. Brake thermal efficiency based on engine speed.

4.4 In-cylinder pressure

The in-cylinder pressure against crank angle for Diesel, BM100, BMBT5, BMBT10, and BMBT15 is shown in (Fig 9) when the engine is fully loaded and running at different speeds. Overall, the pressure curve shape is almost symmetrical. The lower cetane index of butanol blends would cause a long ignition delay, delaying the start of combustion. The predicted maximum pressure was higher because greater amounts of fuel were burnt during the premixed process. Furthermore, the decreased density and viscosity for BMBT5, BMBT10, and BMBT15 could enhance fuel and air mixing (Veza et al., 2023). Consequently, the cylinder peak pressure would be higher. According to the data, and as the figure shows, diesel fuel provides the highest maximum pressure at all engine speeds. The maximum cylinder pressure for D100, BM100, BMBT5, BMBT10, and BMBT15 at full load is 109.55 bar, 106.44 bar, 102.84 bar, 102.34 bar, and 101.45 bar respectively. The pressure increase rate is a commonly used predictor of engine stability and combustion noise, in addition to in-cylinder pressure data.

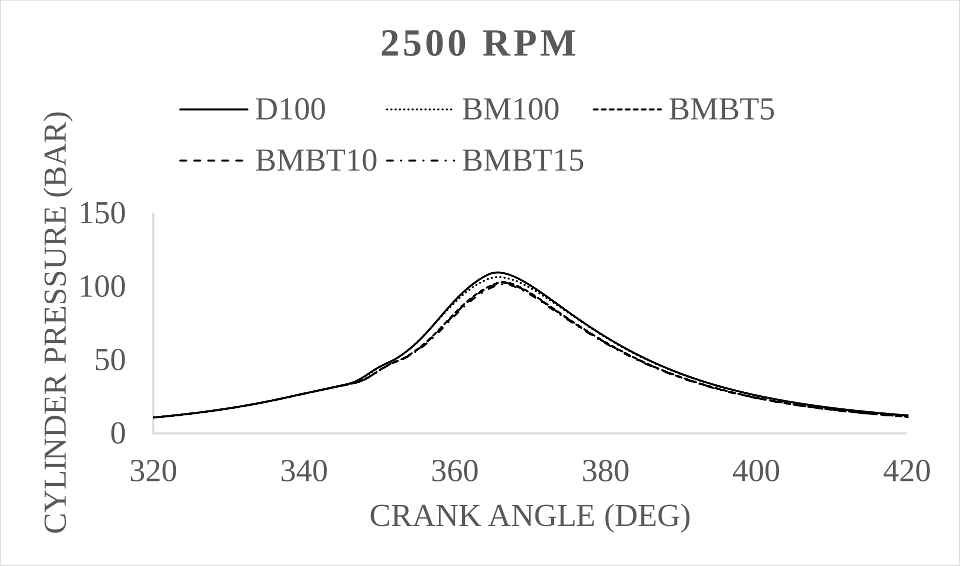

Fig 9. Cylinder pressure based on crank angle.

4.5 Heat release rate

During engine operation, the combustion of the air-fuel combination has an impact on the BTE and BSFC. Figure (10) illustrates how the heat release rate of the tested fuels varies with crank angle. The heat release rates of D100, BM100, BMBT5, BMBT10, and BMBT15 show a similar pattern of heat generation throughout combustion. The highest heat release rate is found in diesel fuel because it has a higher heating value compared to all testing fuel samples, which is a source of the higher heat release rate (Patil & Patil, 2018). However, BMBT5, BMBT10, and BMBT15 obtained lower heat release rate values compared to BM100 due to lower heating values. The maximum heat release rate for Diesel, BM100, BMBT5, BMBT10, and BMBT15 were 24.23 J/deg, 22.29 J/deg, 21.74 J/deg, 21.68 J/deg, and 21.56 J/deg respectively.

4.6 Particulate matter

Figure (11) illustrates how particulate matter varies for prepared fuel blends and diesel engines at various speeds. As compared to regular diesel, the BM100, BMBT5, BMBT10, and BMBT15 dramatically reduced PM by 24.8%, 36.8%, 35.3%, and 33.3%, according to the results. The majority of earlier studies by (Zhang & Balasubramanian, 2016; Ghadikolaei, 2016; Wei et al., 2018) discovered that the use of butanol lowers PM emissions. Da Silva Trindade & Dos Santos, (2017) examined the benefit of using butanol in compression ignition engines and found that it lowers soot emissions, particularly when heavy loads are applied. Butanol improves combustion by raising the oxygen level in blended fuels. This, in turn, prevents new particle production and encourages particle oxidation (O'Connor & Musculus, 2013). As a result, employing butanol is associated with lower PM emissions. According to Xu et al. (2022), particle emissions are mostly determined by the length of the carbon chain.

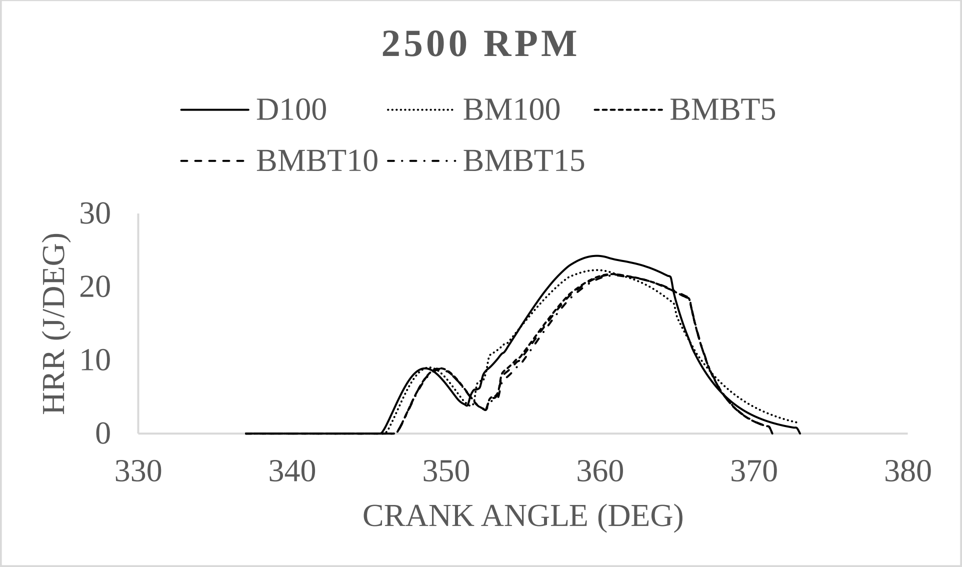

Fig 10. Heat release rate based on crank angle.

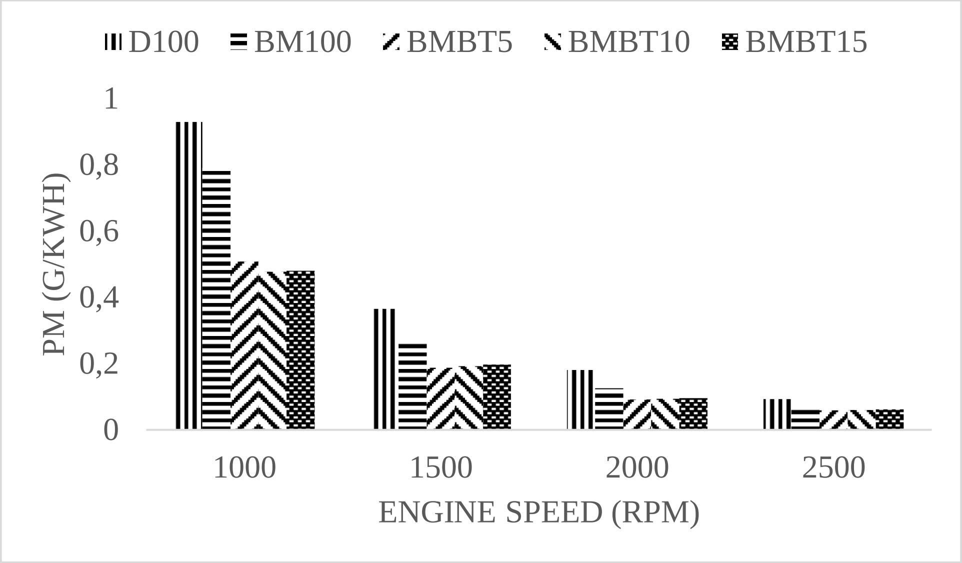

Fig 11. Particulate matter based on engine speed.

4.7 Carbon dioxide emission

Carbon dioxide (CO_2) emissions are plotted against engine speed in Figure (12). When compared to diesel, the emissions from BM100, BMBT5, BMBT10, and BMBT15 have reduced CO_2 (Jeevanantham et al., 2019). According to this viewpoint, pure biodiesel mixture and standard diesel fuel have more carbon atoms than biodiesel mixture-butanol blends when it comes to both quantity and chemical composition. Consequently, it was found that the evaluated tested fuel samples produced lower CO_2 emissions than standard diesel fuel. At maximum speed, the BM100, BMBT5, BMBT10, and BMBT15 demonstrated reductions of 10.3%, 34.1%, 33.5%, and 32.4% compared to standard diesel fuel. Kharkwal et al. (2023) have discovered comparable outcomes.

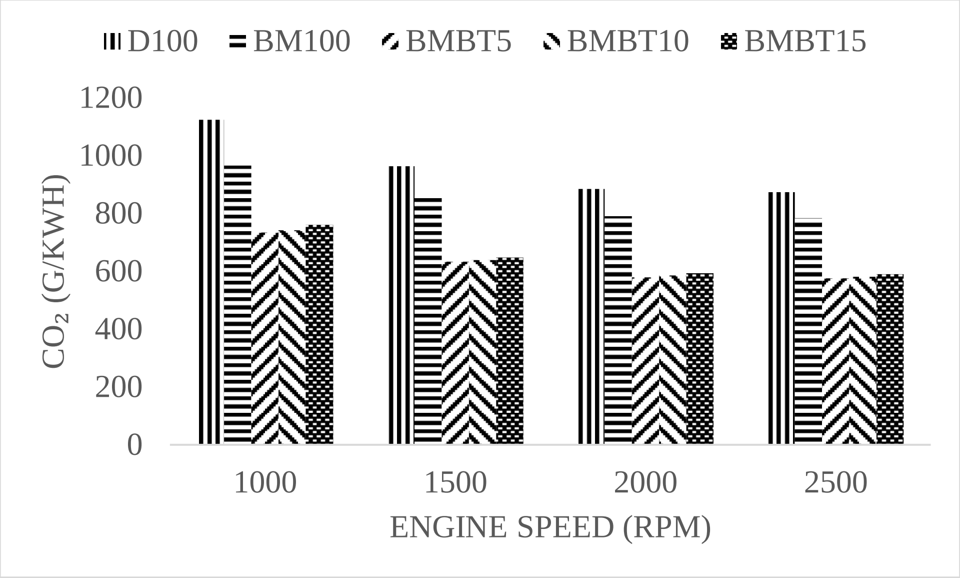

Fig 12. Carbon dioxide is based on engine speed.

4.8 Nitrogen oxide emission

As diesel engines run at different speeds, Figure (13) shows how NO_x differs with prepared fuel mixtures. Nitrogen and oxygen gases react in the atmosphere in the process of combustion, particularly at higher temperatures, producing NO_x. One of the main emitted gases in a diesel engine is NO_x (Zhao et al., 2022). For all studied fuels, NO_x rises as engine speed decreases. According to numerical data, NO_x increases as butanol concentration increases for a particular speed. Diesel has the lowest NO_x because of its higher heating value at all engine speeds, but the NO_x value for biodiesel mixture-butanol blend from 1500 rpm to 2500 rpm is lower compared to BM100. The NO_x emission values for D100, BM100, BMBT5, BMBT10, and BMBT15 are 22.5 ppm, 29.2 ppm, 27.7 ppm, 27.9 ppm, and 28.1 ppm, respectively, at higher engine speeds. Higher NO_x levels for BM100 and various ternary blends could be the result of higher oxygen levels since they promote the generation of NO_x.

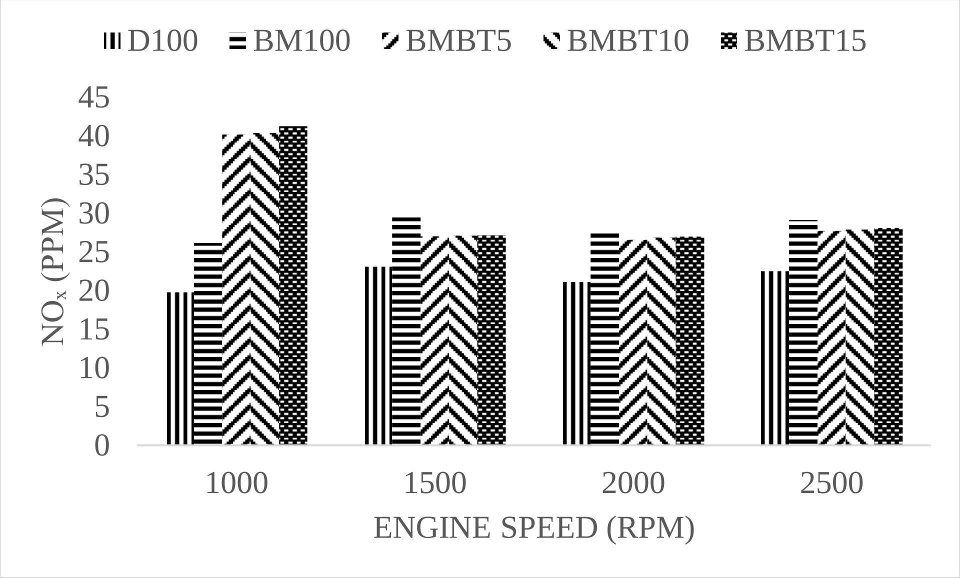

Fig 13. Nitrogen oxide is based on engine speed.

5. CONCLUSION

The performance, combustion, and released gases of four (4) distinct alternative biofuels were predicted numerically in this paper using a suggested computational tool called Diesel-RK. The outcomes were compared to those of standard diesel. Validation of the suggested Diesel-RK results was carried out against experimental findings. Both results from the experiments and numerical technique were in good agreement with each other. The Yanmar generator single-cylinder diesel engine model was used in the numerical analysis conducted under full load conditions and at various engine speeds (1000, 1500, 2000, and 2500 rpm). The study was performed using standard diesel (D100), biodiesel mixture (BM100) (WVB 50%, SB 50%, and butanol 0%), biodiesel mixture and butanol blends (BMBT5) (WVB 80%, SB 15%, and butanol 5%), BMBT10 (WVB 70%, SB 20%, and butanol 10%), and BMBT15 (WVB 60%, SB 25%, and butanol 15%). The following serves as an overview of the current study:

1. The brake-specific fuel consumption of BM100 has been found lower than all biodiesel mixtures-butanol blends, while diesel fuel obtain the lowest value. The brake thermal efficiency of pure biodiesel mixture (BM100) has been improved compared to all testing fuels.

2. The biodiesel mixture and butanol blends have shown closeness of in-cylinder pressure (ICP) and heat release rate (HRR) in the combustion parameters.

3. The CO_2 and HC emissions were increased for standard diesel compared to all green fuels while the NO_x emissions for all green fuels increased compared to standard diesel at all engine speeds.

The biodiesel mixture and butanol blends have the potential to be used as alternative fuels, as demonstrated by the results. The financial profitability aspect of using alternatives is creating job opportunities in rural areas, increasing government income tax, and reducing the country's dependence on crude oil imports. With improvements in technology and this alternative fuel from feedstocks that are available in larger amounts, the environmental cost of HC, particulate, and CO_2 emissions reductions can be achieved. The heating values of green fuels in this study are close to those of conventional diesel in terms of combustion, performance, and emission characteristics, the feasibility of biodiesels in real time has been predicted. Based on the study findings, it appears that the computational tool Diesel-RK holds great potential for accurately and quickly forecasting and analyzing an internal combustion engine's performance, combustion, and emission characteristics. The biodiesel mixture and its blends with butanol can be a good approach to meet the increasing demand for alternative fuel in the future.

ACKNOWLEDGEMENTS

The authors acknowledge the University of South Africa for the support to make this research possible and successful.

NOMENCLATURE

BP	Brake power [kW]	ASTM	American Society of Testing Materials
BSFC	Brake specific fuel consumption [g/kWh]	BMBT5	Biodiesel mixture-5%butanol blend
		BMBT10	Biodiesel mixture-10%butanol blend
BTE	Brake thermal efficiency [%]	BMBT15	Biodiesel mixture-15%butanol blend
ICP	In-cylinder pressure [Bar]	BM100	100%biodiesel mixture
HRR	Heat release rate [J/deg]	BEA	Bosch exhaust analyzer
PM	Particulate matter [g/kWh]	CH_3OH	Methanol
CO_2	Carbon dioxide [g/kWh]	KOH	Potassium hydroxide
NO	Nitrogen oxide [PPM]	SB	Soybean biodiesel

REFERENCES

Ahmad K, Saini P. (2022) Effect of butanol additive with mango seed biodiesel and diesel ternary blends on performance and emission characteristics of diesel engine. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(4):9988-10005. doi.org/10.1080/15567036.2022.2143954.

Al-Dawody M, Rajak U, Jazie AA, Al-Farhany K, Saini G, Verma T N, Nashine P. (2022) Production and performance of biodiesel from Cladophora and Fucus green diesel. Sustainable Energy Technologies and Assessments, 53:102761. doi.org/10.1016/j.seta.2022.102761.

Al-Dawody MF, Bhatti SK. (2013) Optimization strategies to reduce the biodiesel NO_x effect in diesel engines with experimental verification. Energy conversion and management, 68:96-104. doi.org/10.1016/j.enconman.2012.12.025.

Al-Dawody MF, Bhatti SK. (2013) Theoretical modeling of combustion characteristics and performance parameters of biodiesel in DI diesel engine with variable compression ratio. International journal of energy and environment, 4(2)231-242.

Avinash A, Subramaniam D, Murugesan A. (2014). Biodiesel—A global scenario. Renewable and sustainable energy reviews, 29:517-527. doi.org/10.1016/j.rser.2013.09.007.

Babu V, Murthy M. (2017) Butanol and pentanol: The promising biofuels for CI engines–A review. Renewable and Sustainable Energy Reviews, 78:1068-1088. doi.org/10.1016/j.rser.2017.05.038.

Bessah R, Danane F, Alloune R, Abada S. (2023) Biodiesel production feedstocks: current state in Algeria. Journal of Renewable Energies, 26(2):161-177. doi.org/10.54966/jreen.v26i2.1144.

Blanchard R, Richardson DM, O'Farrell PJ, Von Maltitz GP. (2011) Biofuels and biodiversity in South Africa. South African Journal of Science, 107(5):1-8. doi.10.4102/sajs.v107i5/6.186.

Da Silva Trindade WR, Dos Santos RG. (2017) Review on the characteristics of butanol, its production and use as fuel in internal combustion engines. Renewable and Sustainable Energy Reviews, 69:642-651. doi.org/10.1016/j.rser.2016.11.213.

Danane F, Bessah R, Alloune R, Tebouche L, Madjene F, Kheirani AY, Bouabibsa R. (2022) Experimental optimization of Waste Cooking Oil ethanolysis for biodiesel production using Response Surface Methodology (RSM). Science and Technology for Energy Transition, 77:14. doi.org/10.2516/stet/2022014.

Datta A, Mandal BK. (2016) Impact of alcohol addition to diesel on the performance combustion and emissions of a compression ignition engine. Applied thermal engineering, 98:670-682. doi.org/10.1016/j.applthermaleng.2015.12.047.

Datta A, Mandal BK. (2017) Engine performance, combustion and emission characteristics of a compression ignition engine operating on different biodiesel-alcohol blends. Energy, 125:470-483. doi.org/10.1016/j.energy.2017.02.110.

De Castro JF. (2007) Biofuels–an overview. Final Report. Prepared for DGIS/DMW/IB. Environmental Infrastructure and Impact Division, Environment and Water Department, Directorate-General for International Cooperation (DGIS), the Hague, Netherlands.

Devarajan Y, Munuswamy D, Nagappan B, Subbiah G. (2019) Experimental assessment of performance and exhaust emission characteristics of a diesel engine fuelled with Punnai biodiesel/butanol fuel blends. Petroleum Science, 16:1471-1478. doi.org/10.1007/s12182-019-00361-9.

Divakar Shetty AS, Dineshkumar L, Koundinya S, Mane SK. (2017) Experimental investigation on CRDI engine using butanol-biodiesel-diesel blends as fuel. In AIP Conference Proceedings (Vol. 1859, No. 1). AIP Publishing. doi.org/10.1063/1.4990181.

Ghadikolaei MA. (2016) Effect of alcohol blend and fumigation on regulated and unregulated emissions of IC engines—A review. Renewable and Sustainable Energy Reviews, 57:1440-1495. doi.org/10.1016/j.rser.2015.12.128.

Heywood JB. (2018). Internal combustion engine fundamentals. McGraw-Hill Education.

Huang Y, Li Y, Luo K, Wang J. (2020) Biodiesel/butanol blends as a pure biofuel excluding fossil fuels: Effects on diesel engine combustion, performance, and emission characteristics. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 234(13):2988-3000. doi.org/10.1177/0954407020916989.

Imtenan S, Masjuki H.H, Varman M, Fattah IR, Sajjad H, Arbab MI. (2015) Effect of n-butanol and diethyl ether as oxygenated additives on combustion–emission-performance characteristics of a multiple cylinder diesel engine fuelled with diesel–jatropha biodiesel blend. Energy Conversion and Management, 94:84-94. doi.org/10.1016/j.enconman.2015.01.047.

Jeevanantham A K, Nanthagopal K, Ashok B, Ala'a H, Thiyagarajan S, Geo V E, Samuel KJ. (2019) Impact of addition of two ether additives with high speed diesel-Calophyllum Inophyllum biodiesel blends on NOx reduction in CI engine. Energy, 185:39-54. doi.org/10.1016/j.energy.2019.07.013.

Karthickeyan V. (2019) Effect of cetane enhancer on Moringa oleifera biodiesel in a thermal coated direct injection diesel engine. Fuel, 235:538-550. doi.org/10.1016/j.fuel.2018.08.030.

Kharkwal VS, Kesharvani S, Verma S, Dwivedi G, Jain S. (2023) Numerical investigation of engine characteristics of a diesel engine fuelled with ethanol and diethyl ether supplemented diesel-WCO biodiesel blend. Materials Today: Proceedings. doi.org/10.1016/j.matpr.2023.02.106.

Kuleshov AS. (2005) Model for predicting air-fuel mixing, combustion and emissions in DI diesel engines over the whole operating range (No. 2005-01-2119). SAE Technical Paper. doi.org/10.4271/2005-01-2119.

Kuleshov AS. (2006) Use of multi-zone DI diesel spray combustion model for simulation and optimization of performance and emissions of engines with multiple injection (No. 2006-01-1385). SAE Technical Paper. doi.org/10.4271/2006-01-1385.

Kuleshov A, Kozlov AV, Mahkamov K. (2010) Self-Ignition delay Prediction in PCCI direct injection diesel engines using multi-zone spray combustion model and detailed chemistry (No. 2010-01-1960). SAE Technical Paper. doi.org/10.4271/2010-01-1960.

Kumar BR, Saravanan S. (2016) Use of higher alcohol biofuels in diesel engines: A review. Renewable and Sustainable Energy Reviews, 60:84-115. doi.org/10.1016/j.rser.2016.01.085.

Lapuerta M, Rodríguez-Fernández J, Fernández-Rodríguez D, Patiño-Camino R. (2018) Cold flow and filterability properties of n-butanol and ethanol blends with diesel and biodiesel fuels. Fuel, 224: 552-559. doi.org/10.1016/j.fuel.2018.03.083.

Mahmudul HM, Hagos FY, Mamat R, Adam AA, Ishak W FW, Alenezi R. (2017) Production, characterization and performance of biodiesel as an alternative fuel in diesel engines–A review. Renewable and Sustainable Energy Reviews, 72:497-509. doi.org/10.1016/j.rser.2017.01.001.

Mbohwa C, Mudiwakure A. (2013). The status of used vegetable oil (UVO) biodiesel production in South Africa. In Proceedings of the world congress on engineering, 1: 3-5.

Nour M, Attia AM, Nada SA. (2019a) Combustion, performance and emission analysis of diesel engine fuelled by higher alcohols (butanol, octanol and heptanol)/diesel blends. Energy conversion and management, 185:313-329. doi.org/10.1016/j.enconman.2019.01.105.

Nour M, Attia AM, Nada SA. (2019b) Improvement of CI engine combustion and performance running on ternary blends of higher alcohol (Pentanol and Octanol)/hydrous ethanol/diesel. Fuel, 251: 10-22. doi.org/10.1016/j.fuel.2019.04.026.

O'Connor J, Musculus M. (2013) Post injections for soot reduction in diesel engines: a review of current understanding. SAE International Journal of Engines, 6(1):400-421. doi:10.4271/2013-01-0917.

Patil VV, Patil RS. (2018) Investigations on partial addition of n-butanol in sunflower oil methyl ester powered diesel engine. Journal of Energy Resources Technology, 140(1):012205. doi.org/10.1115/1.4037372.

Pitchaiah S, Juchelková D, Sathyamurthy R, Atabani A E. (2023) Prediction and performance optimisation of a DI CI engine fuelled diesel–Bael biodiesel blends with DMC additive using RSM and ANN: Energy and exergy analysis. Energy Conversion and Management, 292:117386. doi.org/10.1016/j.enconman.2023.117386.

Pradhan A, Mbohwa C. (2014) Development of biofuels in South Africa: Challenges and opportunities. Renewable and Sustainable Energy Reviews, 39:1089-1100. doi.org/10.1016/j.rser.2014.07.131.

Prbakaran B, Viswanathan D. (2018) Experimental investigation of effects of addition of ethanol to bio-diesel on performance, combustion and emission characteristics in CI engine. Alexandria Engineering Journal, 57(1):383–389. doi.org/10.1016/j.aej.2016.09.009.

Ramuhaheli S, Veeredhi VR, Enweremadu CC. (2022) The performance and emission characteristics assessment of hybrid biodiesel/ethanol blends in a diesel engine. Environmental and Climate Technologies, 26(1):670-683. doi.org/10.2478/rtuect-2022-0051.

Rendleman CM, Shapouri H. (2007) New technologies in ethanol production (No. 1473-2021-026). doi.org/10.22004/ag.econ.308483.

Semwal S, Arora AK, Badoni RP, Tuli DK. (2011) Biodiesel production using heterogeneous catalysts. Bioresource Technology, 102(3):2151-2161. doi.org/10.1016/j.biortech.2010.10.080.

Singh R., Singh S, Kumar M. (2020) Impact of n-butanol as an additive with eucalyptus biodiesel-diesel blends on the performance and emission parameters of the diesel engine. Fuel, 277:118178. doi.org/10.1016/j.fuel.2020.118178.

Soudagar MEM, Khan HM, Khan TY, Razzaq L, Asif T, Mujtaba MA, Safaei MR. (2021) Experimental analysis of engine performance and exhaust pollutant on a single-cylinder diesel engine operated using moringa oleifera biodiesel. Applied Sciences, 11(15):7071. doi.org/10.3390/app11157071.

Swarna S, Swamy MT, Divakara TR, Krishnamurthy KN, Shashidhar S. (2022) Experimental assessment of ternary fuel blends of diesel, hybrid biodiesel and alcohol in naturally aspirated CI engine. International Journal of Environmental Science and Technology, 19(9):8523-8554. doi.org/10.1007/s13762-021-03586-7.

Veza I, Hoang AT, Yusuf AA, Herawan SG, Soudagar MEM, Samuel OD, Silitonga AS. (2023) Effects of Acetone-Butanol-Ethanol (ABE) addition on HCCI-DI engine performance, combustion and emission. Fuel, 333:126377. doi.org/10.1016/j.fuel.2022.126377.

Wei L, Cheung CS, Ning Z. (2018) Effects of biodiesel-ethanol and biodiesel-butanol blends on the combustion, performance and emissions of a diesel engine. Energy, 155:957-970. doi.org/10.1016/j.energy.2018.05.049.

Woschni G. (1967) A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine (No. 670931). SAE Technical paper. doi.org/10.4271/670931.

Xiao H, Guo F, Wang R, Yang X, Li S, Ruan J. (2020) Combustion performance and emission characteristics of a diesel engine fueled with iso-butanol/biodiesel blends. Fuel, 268:117387. doi.org/10.1016/j.fuel.2020.117387.

Xu L, Wang Y, Liu D. (2022) Effects of oxygenated biofuel additives on soot formation: A comprehensive review of laboratory-scale studies. Fuel, 313:122635. doi.org/10.1016/j.fuel.2021.122635.

Zhao W, Yan J, Gao S, Lee TH, Li X. (2022) The combustion and emission characteristics of a common-rail diesel engine fueled with diesel and higher alcohol blends with a high blend ratio. Energy, 261:124972. doi.org/10.1016/j.energy.2022.124972.

Zhang ZH, Balasubramanian R. (2014) Influence of butanol addition to diesel–biodiesel blend on engine performance and particulate emissions of a stationary diesel engine. Applied Energy, 119:530-536. doi.org/10.1016/j.apenergy.2014.01.043.

Zhang ZH, Balasubramanian R. (2016). Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends. Applied energy, 163:71-80. doi.org/10.1016/j.apenergy.2015.10.173.