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Effects of Waste Cooking Oil Biodiesel on Performance, Combustion and Emission Characteristics of a Compression Ignition Engine

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Abstract

With their higher sustainability index, biofuels, environmentally-friendly and renewable nature is a viable alternative energy source in the transportation sector. This study presents the effect of waste cooking oil (WCO) biodiesel on performance, combustion, and emission from a compression ignition engine. The biodiesel was blended with diesel in varying proportions of 5% biodiesel and 95% diesel (designated as B5), 10% biodiesel in diesel (B10), 15% biodiesel in diesel (B15), 20% biodiesel in diesel (B20), 50% biodiesel in diesel (B50), and 85% biodiesel in diesel (B85). Simulation of a 2-cylinder diesel engine fueled with diesel, biodiesel blends and pure biodiesel was carried out using Ricardo Wave software and the results obtained were validated. The engine speed was varied from 1200 rpm to 3200 rpm at full load condition using a positive valve overlap of 32°. Performance results showed that WCO biodiesel blends at 1200 rpm produce brake-specific fuel consumption of, 0.240109 kg/kWhr, 0.241996 kg/kWhr, 0.244331 kg/kWhr, 0.24661 kg/kWhr, 0.26089 kg/kWhr, 0.27947 kg/kWhr and 0.28798 kg/kWhr for B5, B10, B15, B20, B50, B85 and B100 respectively, as compared to 0.239383 kg/kWhr of diesel fuel while the brake power and torque reduced at full load with varying speed. Combustion analysis showed similar trends between diesel and biodiesel blends whereas biodiesel blends produced shorter ignition delay, shorter combustion duration, and lower heat release rate. Emission levels of CO, reduced by 1%, 10%, 15%, 22%, 48%, 68% and 74% with B5, B10, B15, B20, B50, B85 and B100 respectively at 1600 rpm when compared to diesel fuel. HC emission was reduced by 9% with B100. NO_x levels slightly increased when B5, B10, B15, and B20 at 1200 rpm and B10 and B15 at 1600 rpm were fueled in the engine. The exhaust gas temperature (EGT) of B5, B10 at 1600 rpm was higher than diesel fuel and B5, B10 at 2400 rpm to 3200 rpm EGT was higher than diesel fuel. Generally, biodiesel blends showed better emission levels and other combustion and performance levels are within acceptable limits.

Keywords

Diesel engine; biodiesel; waste cooking oil biodiesel; engine performance; combustion; emissions

1. Introduction

Internal combustion engines precisely diesel engine is crucial to the economic and socioeconomic activities worldwide. Diesel engines are used in agriculture, transportation, mining, power generation and other sectors of the economy. Internal combustion engines are primarily fueled with fossil fuels with their associated gaseous emissions depleting the ozone and contributing to global warming. Biofuels prefer sustainable alternative fuel to conventional fuel with reduced gaseous emission which grossly affects the global environment. Several nations have legislated that conventional diesel should be blended with a proportion of biofuels, to enhance the production and usage of biofuels. The utilization of biofuel provides the generation of employment and technological development in developing countries, which will improve the economy of these countries. Biodiesel can be obtained from soybeans, jatropha, palm kernel, canola, beef tallow and waste cooking oil, which are readily available and renewable in Nigeria. However, waste cooking oil provides a means to convert waste to wealth and reduce the competition between using edible oil for energy generation instead of food production. This reduces waste and increases wealth in terms of direct and indirect jobs created when the waste cooking oil is used to produce biodiesel. Biodiesel provides lower cost, lower gaseous emission levels of Particulate Matter (PM), Hydrocarbon (HC), Carbon monoxide (CO), and net Carbon dioxide (CO_2) emissions in Nigeria and the world at large. With the continually increasing demand for diesel fuel to run diesel engines while considering the demand, cost, and gaseous emissions, and the contribution to wealth creation in developing countries like Nigeria. Biodiesel and biodiesel blends (i.e., a mixture of conventional diesel with biodiesel at different proportions) are more environment-friendly and non-toxic, it also improves the mechanical efficiency of the engines, and above all can also lead to a reduction in poverty among the rural dwellers which will help achieve the Sustainability Development Goals (SDGs) of the United Nations Organization. Several investigations have reported that using biodiesel in engines reduces the emission of Sulphur dioxide, HC, CO, Particulate Matter (PM) and CO_2 emissions on a life-cycle basis. It results in improved lubricity, lower visible smoke and zero aromatics. In developing countries like Nigeria, access to engine testbeds to investigate emission, performance and combustion from engines is not readily available; therefore employing simulation software to carry out analysis becomes a great alternative to ascertain the viability of locally produced biodiesel.

Manikandan G, et al. [1] reviewed the waste cooking oil (WCO) as a feedstock for biodiesel. They examined WCO as a tool to address social, technological, and economical challenges. Their review showed that WCO would save 10% of importation costs in India, and WCO is suitable and sustainable as an alternative to diesel fuel. Also they revealed that WCO production is cheaper than conventional diesel fuel. [2] evaluated the effect of palm oil biodiesel in a diesel engine. They used a Lombardini 2-cylinder, four-stroke direct injection diesel engine with a compression ratio of 22.8 was developed using Ricardo Wave software; the simulation was done at full load condition with varying speeds of 1200 rpm to 3200 rpm at 400 rpm intervals. Their results showed that biodiesel utilization resulted in a reduction of CO, HC and NO_x emissions. They concluded that biodiesel is a viable and sustainable alternative to conventional diesel fuel. [3] conducted a sustainability study of waste cooking oil as a source of biofuel. They produced biofuel(biodiesel) from WCO using the transesterification process and the biodiesel obtained was analyzed experimentally in the laboratory. Their analysis showed that WCO biodiesel properties were within acceptable limits and beneficial to the environment and economy because its biodegradable, more economical than diesel fuel and environmentally friendly. [4] evaluated the environmental and enviro-economic aspects of waste cooking oil biodiesel usage in a direct injection diesel engine. They used a single-cylinder, four-stroke, water-cooled, direct-injection diesel engine using a hydraulic dynamometer to vary the load and exhaust emission analyzer. The engine was operated at full load condition with varying speeds of 1000 to 3200 rpm at 200 rpm intervals. Their results showed that environmental and enviroeconomic analysis indicated that a higher concentration of biodiesel in the blend (B100) was better than lower ones like B20. [5] analyzed the effect of waste cooking oil blending with diesel fuel in a diesel engine. They blended waste cooking oil with diesel fuel designated as B10, B20 and B30. Experiments were conducted using a Torpedo D 6806 four-cylinder four-stroke, direct injection, air cooled engine rated at 49 kW at 2200 rpm. Their results showed that WCO blends are like diesel fuel with reduced CO, CO_2, and HC emissions, while performance results were similar. They also observed no significant difference in NO_x emission between the diesel and B30 blends. [6] Discussed the effect of waste cooking oil's quality on biodiesel's properties. They used a single-cylinder stationary engine loaded using an alternator; CO, HC & NO emissions were measured using AVL Digas 444 gas analyzer and AVL 437 smoke meter used to measure the smoke value. Their results indicated that WCOs emitted slightly higher CO than biodiesel from unused oil but NO and smoke emissions were similar. They concluded that due to WCO's degradability and having no adverse effect on engine performance and emission, WCO could be considered a promising feedstock in the sustainable production of biodiesel.

Al Doori Ali et al., [7] carried out a comparative analysis of biodiesel from grilled chicken waste oil derived from an animal-based source (GCWOB) and waste cooking oil derived from sunflower (WCOB); the engine test was done using a one-cylinder 4-stroke water cooled direct injection Yammar TF 120 diesel engine with a maximum power of 12 kW at 2400 rpm. Their results showed that using biodiesel increased BSFC and reduced BP compared to diesel fuel; however, GCWOB had better production yield, fuel property and engine performance as against WCOB. [8] investigated the autoignition behavior and emission from jatropha, tire pyrolysis oil, algae, palm oil and waste cooking oil biodiesel. Their experiment was conducted using a 1-cylinder air-cooled rapid compression machine with a compression ratio 19.5. Their results revealed that ignition delay and emission in biodiesel blends are influenced largely by fuel mixing concentration, injection pressure and ambient temperature which affects the autoignition and combustion. [9] investigated the impact of injection timing and duration on engine brake power and NO_x using Diesel-RK simulation software. They operated the engine at different engine speeds of 1000, 1500, 2000, 2500, 3000 and 4000 rpm, at different injection timing of 10° CA-bTDC, 5° CA-bTDC and 0° CA-TDC and different injection duration of 20°, 25°, 30°, 35° and 40° CA. From their results NO_x emission was reduced in the greater injection durations while the brake power decreased at those injection durations. Consequently, as the brake power increased, the NO_x emissions increased. [10] analyzed the combined effect of a catalytic reduction device with waste frying oil-based biodiesel on NO_x emission. In their experiment, they used a four-stroke, air-cooled compression ignition engine operated at a constant speed of 1900 rpm fueled with B0, B5 B20, B30, B70 and B100 coupled with a Megatech DG2 dynamometer varying the load from 25%, 50%, 75% and 100%. A PCA 3 Bacharach Gas Analyzer was used. Their results revealed that NO_x emission increased with an increase in load and reduced significantly with the use of the catalytic converted device. [11] investigated the effects of biodiesel, biodiesel binary blends, hydrogenated biodiesel and injection parameters on NO_x and soot emissions in a turbocharged diesel engine. They used a multi-zone phenomenological model to predict the test fuels' performance, combustion and emission characteristics. The results were validated with experimental data obtained from a four-cylinder, fixed geometry turbocharged diesel engine. Their model shows a maximum prediction error of 7% and 18% for NO and soot emission. They stated that the biodiesel-NO_x penalty could be reduced by 35% by restoring the start of injection (SOI) to that of diesel fuel. Also, their results indicated an 18% reduction in NO_x emission with biodiesel usage. Their model predictions recommended that the hydrogenated biodiesel could be injected with the same SOI of diesel fuel to address the NO_x-penalty in biodiesel-fueled engines. [12] performed experiments and simulations to ascertain the effect of Methyl waste cooking oil (MEWCO) blends on emission and performance. The test fuel blend uses 10%, 20%, 30% and 100% MEWCO are tested on a constant-speed diesel engine. Their experimental and simulated results are in good agreement. Their results indicated that BTE and NO_x were reduced with MEWCO, but with a slight increase in BSFC. In addition, they observed a 10% decrease in exhaust temperature when MEWCO was used and as the blending ratio of MEWCO increases the Carbon Emissions increase. [13] revealed that Waste Cooking Oil biodiesel (WCOME) could be a viable alternative to conventional diesel fuel. The ever-growing world population, depleting fossil fuel and environmental concerns. Their review indicated the viability of WCOME notwithstanding the slight increase in NO_x emission and brake-specific consumption. Azad et al. [14] did a comparative study of diesel engine performance and emission with soybean and waste oil biodiesel fuel. Their experimental test was done on a 4-cylinder Kubota 4-stroke diesel engine. The tested biodiesels were mixed with ultra-low Sulphur diesel at varying proportions of B5, B10, B20 and B50. Their results showed that soybean blends i.e., B5 and B10 were better than waste oil biodiesel about performance and emission levels. Therefore recommended that B10 of soybean would be an acceptable alternative for diesel fuel since it showed more consistent desired results from all the analyses done. [15] investigated the effects of fish oil methyl esters on performance and emission characteristics. They observed an increase in BSFC, exhaust temperature and NO_x with biodiesel blends but a reduction in CO and HC emissions. The B20 thermal efficiency of 31.74% was higher than that of diesel fuel. [16] investigated the effect of waste cooking oil biodiesel on the emissions of a diesel engine. Their results showed a decrease in HC, CO and PM but NO_x increased with biodiesel. [17] They produced non-edible vegetable oil from Oleander, Kusum and Bitter Groundnut seed in their study. After extracting the biodiesel, they used it to run a four-cylinder, four-stroke diesel engine attached to an eddy current dynamometer at different engine speeds and full load conditions. Their results indicated that the Oleander biodiesel produced the highest brake thermal efficiency and lowest brake specific fuel consumption against Kusum and Bitter Groundnut biodiesel. The Bitter Groundnut Biodiesel obtained lesser emissions compared to Oleander and Kusum Biodiesel. From their results, they concluded that Oleander, Kusum, and Bitter Groundnut had the potential to become an additional source of fuel in the future. [18] evaluated the performance of a diesel engine fueled by Biodiesel extracted from a waste cooking oil. The tests were performed on a four-stroke single-cylinder diesel engine loaded at varying speeds between 1200-2600 rpm, fueled with waste cooking oil. The results they obtained showed that higher biodiesel content in the test fuel led to an increase in NO_x emissions and employing exhaust gas recirculation strategy affected the NO_x emission more than the fuel composition. They also noted that increasing the engine speed increased brake thermal efficiency, equivalence ratio, fuel consumption rate, and exhaust gas temperature, while CO_2, and CO decreased for the four tested fuels. Using a one-cylinder four-stroke diesel engine [19] investigated the effects of biodiesel fuel emissions. The biodiesel was produced from palm oil, algae, jatropha and WCO and blended with diesel fuel at 10% and 20% respectively. The exhaust gas emissions were analyzed at engine loads of 1, 2, 3 and 4 kW and an engine speed of 1500 rpm was used. The physicochemical properties of Cetane Number, flash point were higher in biodiesel than in diesel oil indicating better combustion and safer storage. In contrast, the viscosity and density of biodiesel were higher. Their emission results revealed that CO, HC, and smoke opacity were reduced using biodiesel. In addition, CO_2 is reduced with biodiesel except biodiesel from WCO. The NO_x emission increased slightly with all biodiesel fuel compared to diesel oil. [20] conducted an experiment on a stationary diesel engine using biodiesel obtained from waste cooking oil to investigate its exhaust compositions. They used a Kubota (model V3300) multi-cylinder diesel engine with a CODA 5 exhaust gas analyzer to measure the gaseous emissions from the engine and an MPM-4M particulate meter to measure the Particulate Matter (PM) emission. The engine was operated at full load condition with varying engine speeds from 1200 rpm to 2400 rpm at intervals of 200 rpm. Results revealed that CO and PM emissions decreased significantly with biodiesel than diesel oil. In contrast, NO_x emission increased with biodiesel as compared to diesel oil, which they attributed to biodiesel's higher cetane number, higher oxygen content and combustion temperature. [21] examined the emission and combustion characteristics using conventional diesel and Vegetable blends. Their experimental tests showed lower HC and CO with vegetable blend as against diesel fuel. The NO_x, CO_2 emission and smoke opacity increased with vegetable blend as against diesel fuel. It was also noted that combustion duration showed a similar trend among vegetable blends and conventional diesel fuel.

The novelty of this study is using Ricardo Wave simulation software was used to evaluate the performance, combustion and emission features emanating from C.I. engine-fueled diesel fuel, B5 (5% biodiesel, 95% diesel), B10, B15, B20, B50, B85, B100 was investigated under constant load with varying speeds using positive valve overlap. Due to the high cost of engine test beds and access to them in developing countries utilizing technology to evaluate the viability of biodiesel can spark local interest in the subject and investment to use biodiesel in achieving the SDGs in developing countries. Also, positive valve overlap has rarely been employed in diesel engines. Hence, this research aims to evaluate the effect of waste cooking oil biodiesel on performance, combustion and emission in a compression ignition engine incorporating positive valve overlap.

2. Simulation Model

The simulation models are based on thermodynamic models and fluid dynamic models. Using the first law of thermodynamic performance parameters of the engine are evaluated. [22] stated that engine friction and heat transfer are considered from empirical relations obtained from experimental data, classified as single-zone and multi-zone models. Internal combustion engine combustion process simulation also uses multi-zone models. These models are derived from numerical analysis of the conservation of mass, energy, momentum, and species equations. The simulation was performed using Ricardo Wave commercial software whose fundamental governing equations as found in Ricardo Wave 2017.1 notes are as follows:

Conservation of Mass

$$mass = \frac{d_m}{d_t} = \sum \dot{m} \tag{1}$$

Conservation of Energy

$$energy = \frac{de_T}{d_t} = -p\frac{d_V}{d_t} + \frac{dQ_{ht}}{d_t} + \sum_j \dot{m}_j h_j \tag{2}$$

Conservation of Momentum

$$momentum = \frac{d_{mu}}{d_t} = -A\frac{d_p}{d_x}d_x + \sum \dot{m}u - -p\frac{d_V}{d_t} + \frac{dQ_{ht}}{d_t} \tag{3}$$

The solution of these equations is obtained using the finite difference method. The explicit technique is utilized in the time-differencing while the Courant condition governs the timestep.

The general combustion equilibrium equation solved by the WAVE property pre-processor is:

$$A^*(uN_2 + vO_2 + wCO_2 + xH_2O) + B^*(C_C H_H O_O N_N) \rightarrow aCO + bCO_2 + cH + dH_2 + eH_2O + fN_2 + gNO + hO + iO_2 + jOH + kN \tag{4}$$

3. Methodology

This study simulated a 2-cylinder, Lombardini diesel engine operation using Ricardo Wave 2017.1 software to analyze the performance, combustion, and emission features of waste cooking oil biodiesel-diesel blends. The WCO biodiesel blends of B5, B10, B15, B20, B50, B85 and B100 were tested at engine loads of 100% and for a range of speeds from 1200 rpm to 3200 rpm. Performance parameters analyzed from the simulation are brake-specific fuel consumption, brake thermal efficiency, brake power, brake torque, and exhaust gas temperature. Combustion and emission parameters include ignition delay, combustion duration, combustion phasing, fuel mass burned, heat release rate, CO, HC, and NO_x.

Table 1 below shows the engine specification used in this study while the physiochemical properties of the different fuel blends are shown in Table 2 obtained from the previous work of [23].

Table 1 Engine Specification.

Lombardini LDW 702	
Cylinders (N)	2
Bore(mm)	75
Stroke(mm)	77.6
Displacements(cm^3)	686
Compression rate (-)	22.8:1
Cooling System	Liquid Coolant
Maximum Speed (rpm)	3600
Maximum torque (Nm) @ 2000 rpm	40.5
Injector Timing	11° +/- 1°
Injector Opening pressure (bar)	140 +/- 15

Table 2 Properties of Test fuels.

Property	**Diesel**	**B5**	**B10**	**B15**	**B20**	**B50**	**B85**	**B100**
Density @ 15.5°C (kg/m^3)	827.2	831.6	836.0	840.4	844.9	871.4	902.3	915.5
Viscosity @ 40°C (mm^2/s)	3.3230	3.5316	3.7402	3.9489	4.1575	5.4092	6.8695	7.4954
Viscosity index	90.0	94.3	98.6	102.9	107.2	133.0	163.1	176.0
Pour Point (°C)	0	0.2	0.3	0.5	0.6	1.5	2.6	3.0
Flash Point (°C)	68.5	73.7	78.9	84.0	89.2	120.3	156.5	172.0
Cloud Point(°C)	8.00	7.65	7.3	6.95	6.60	4.50	2.05	1.00
Lower Heating Value [kJ/kg]	45300	44928	44584	44214	43898	41836	39430	38400
Cetane Number [-]	49	49.6	50.2	50.6	51	53.5	56.4	57

4. Results and Discussion

The model created in Ricardo Wave software for performance, combustion and emission has been validated by comparing the simulation results obtained with that obtained by Atabani [24] under similar operating conditions. Table 3 presents this comparison of results.

Table 3 Comparison of some simulation results to values obtained in the literature.

Parameters	**Present Model**	**Atabani [23]**	**Error (%)**
Torque	115	128	10
Brake Power	12.14	13.00	6.6
BTE	35.30	N/A	-
CO ppm	15.68	N/A	-

NO_x ppm	117	120	2.5

The high error with BSFC in the validation is associated with incomplete data used in the validation process. Because the available engine data sheet about the engine used by Atabani [24] does not contain some parameters that will be used, hence some assumptions were made to complete the validation.

4.1 Performance Analysis

4.1.1 Brake-Specific Fuel Consumption (BSFC)

The BSFC of an engine measures fuel efficiency and depends on the fuel's density, viscosity, and heating value. Figure 1 shows that an increase in the biodiesel blend ratio increases the BSFC compared to diesel fuel. Several kinds of literature have noted that the increase in BSFC with biodiesel is associated with its lower heating values, thus requiring more fuel to be burned to compensate for its lower heating value [12, 25, 26]. Results also show that BSFC increased with an increase in engine speed from 1600 rpm to 3200 which is as a result higher density and lower calorific value. Atabani [24] also reported a similar trend to the results obtained in this study.

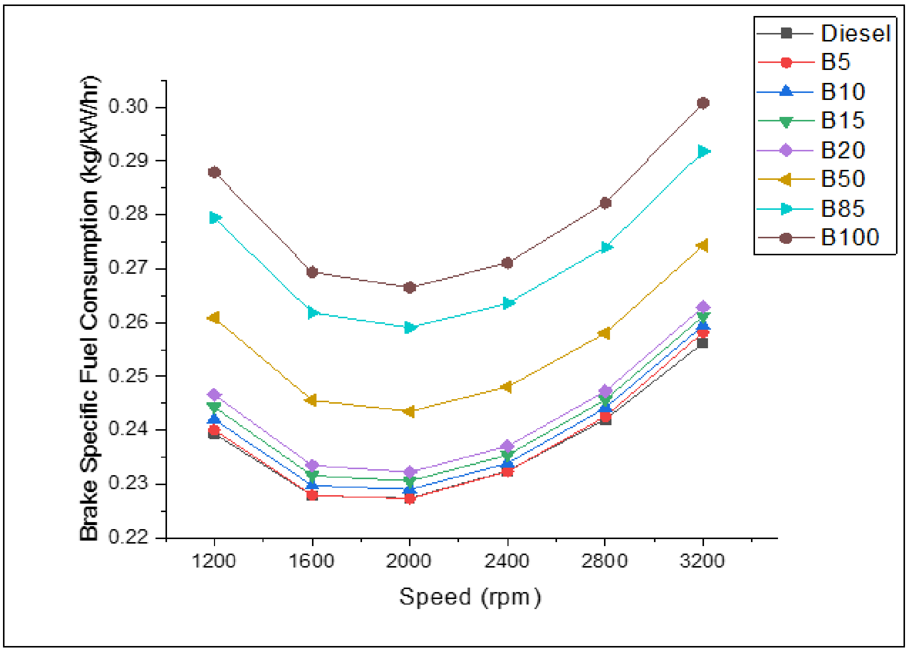

Figure 1 Variation of BSFC with respect to Speed.

4.1.2 Brake Thermal Efficiency (BTE)

The BTE indicates how well the engine converts the energy from the fuel into useful mechanical energy. Figure 2, showing the variation of brake thermal efficiency with speed for diesel and the biodiesel blends indicated that the BTE of all tested fuels increased with an increase in speed from 1200 rpm to 2000 rpm and then decreased as the speed increased. This is expected since as the speed increases more oxygenated fuel is injected thereby enhancing the energy conversion. The BTE of Biodiesel blends was higher than diesel fuel at all speed levels. The maximum BTE of 35.12%

was obtained for anIncrease in BTE could be due to the enhanced combustion process resulting from increased oxygen content [26, 27]. However, all the blends display a maximum BTE at about 2000 rpm.

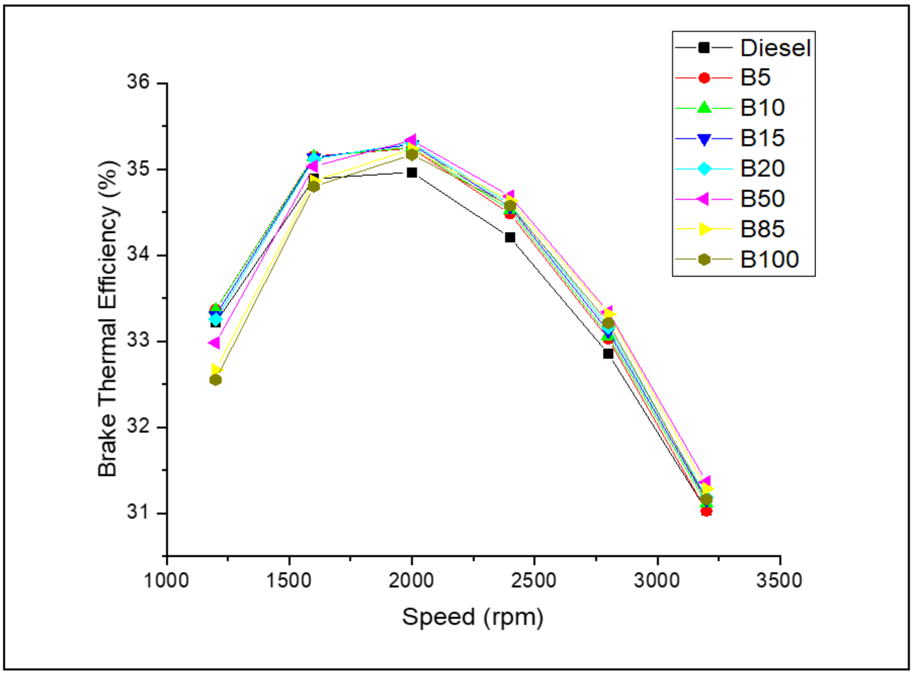

Figure 2 Variation of BTE with respect to Speed.

4.1.3 Brake Torque

In Figure 3 the variations in brake torque are shown, where it is observed that B5 has the maximum brake torque of 42.2 Nm at 1600 rpm. Generally, the brake torque reduces with an increase in biodiesel blend ratio because of its reduced lower heating value compared to that of conventional diesel fuel [28]. Therefore, the higher the fuel's heating value, the higher the brake torque. The brake torque generally increases with increasing speed up to a maximum value and then decreases with an increase in speed.

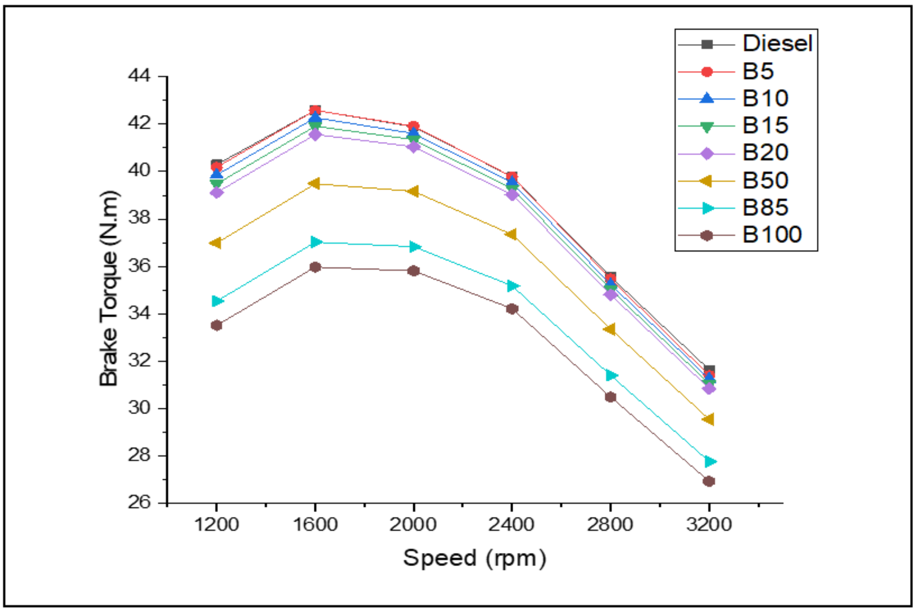

Figure 3 Variation of Torque with respect to Speed.

4.1.4 Brake Power

The brake power is the available power at the crankshaft of an engine. The maximum brake power of 10.47 kW was obtained at 3200 rpm when diesel is used in the engine. In Figure 4 an increase in speed produces a corresponding increase in brake power. However, biodiesel blends show a relative reduction in terms of brake power when compared to diesel fuel.

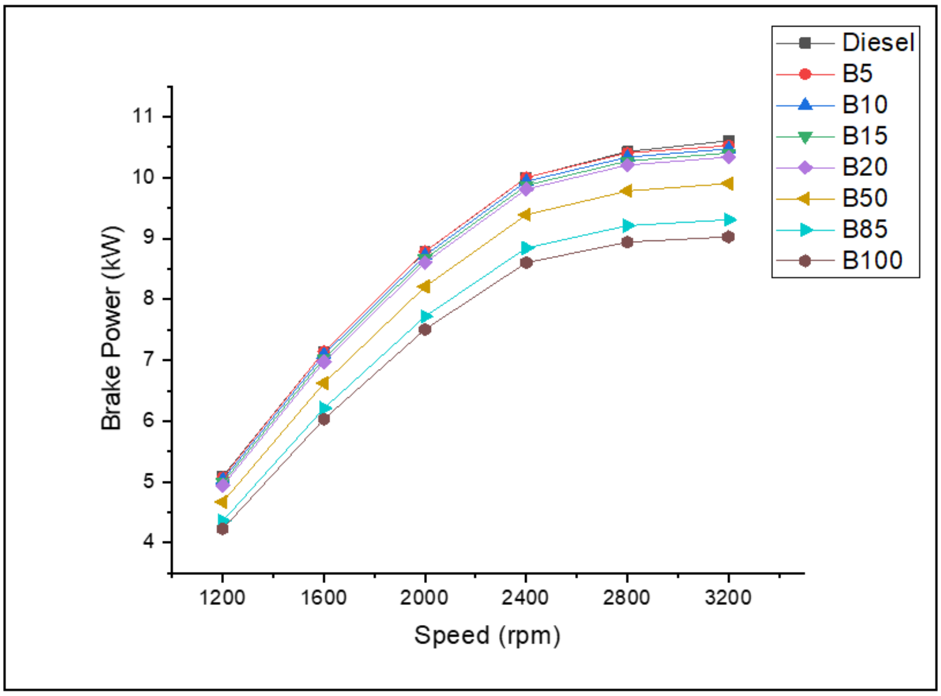

Figure 4 Variation of Brake Power with respect to Speed.

4.2 Combustion Analysis

4.2.1 Ignition Delay

The ignition delay in a diesel engine denotes the time fuel injection begins in the engine and the start of combustion. In the combustion process, the ignition delay is the first phase. Figure 5 shows the variation in ignition delay, indicating a reduction in ignition delay with biodiesel blend compared to diesel fuel. This phenomenon is because of the higher viscosity, especially because the higher cetane number in biodiesels causes shorter ignition delay. Several researchers have also observed this phenomenon [29-31].

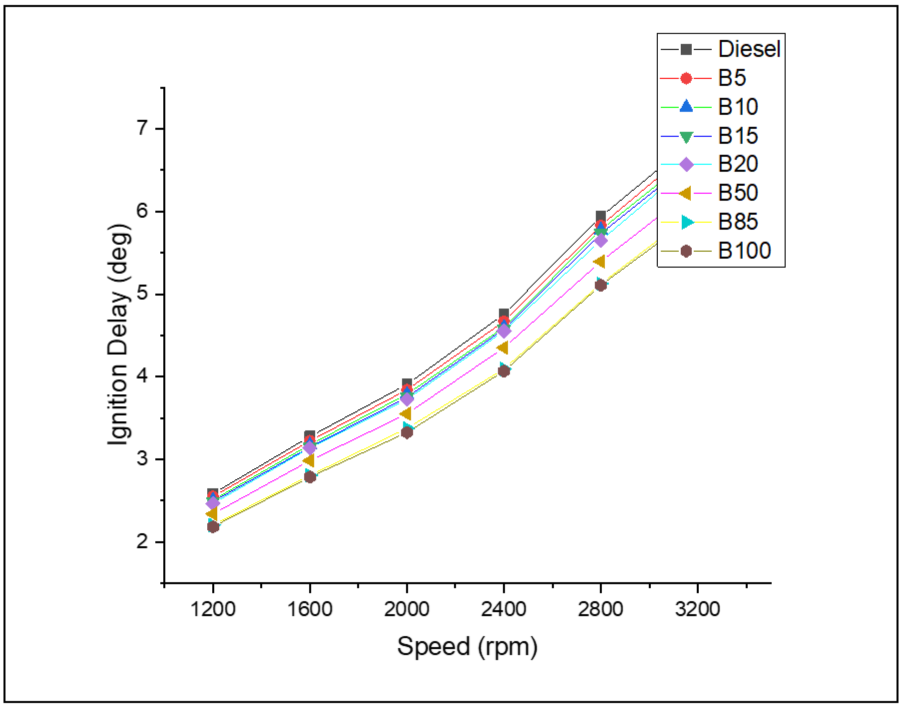

Figure 5 Variation of Ignition Delay with respect to Speed.

4.2.2 Onset of Combustion (CA_10)

The CA_10 indicates the time ignition of fuel begins in a diesel engine. Figure 6 shows the variation in the onset of combustion of diesel and biodiesel blends. It was observed that the onset of diesel combustion is lower than that of biodiesel blends at all speed levels except 1200 rpm in which B85 and B100 are lower than that of diesel fuel. This phenomenon is because of the physiochemical properties of the fuel.

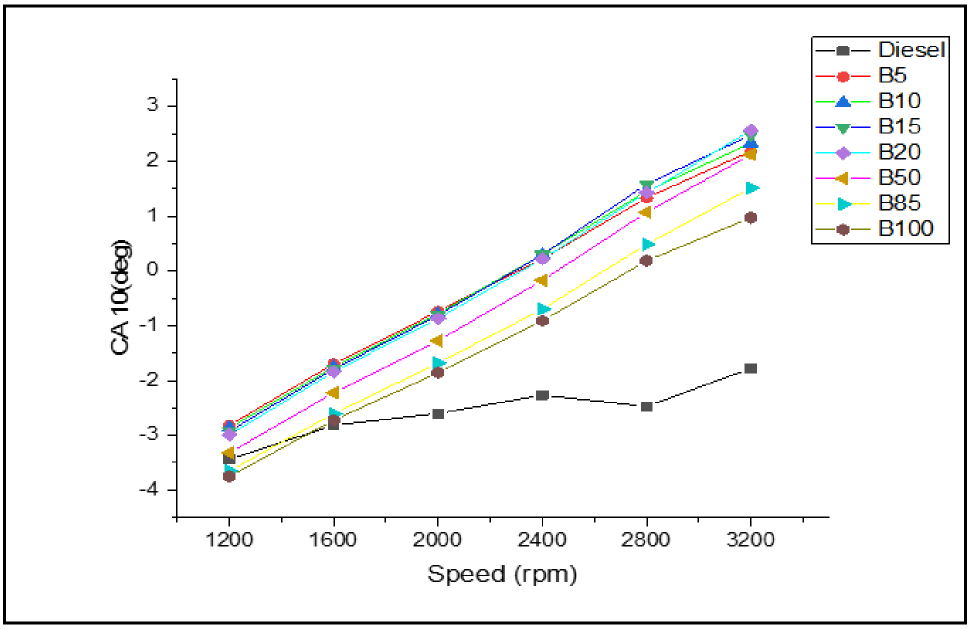

Figure 6 Variation of CA 10 with respect to Speed.

4.2.3 Combustion Phasing (CA_50)

Combustion phasing denotes the crank angle during the engine cycle where 50% of the energy content of the fuel has been released or the fuel has been burned. CA_50 influences the engine efficiency and output torque of the diesel engine. Firstly, the combustion phasing increases with increasing speed for all the fuel blends and pure diesel fuel, as shown in Figure 7. Secondly, for blends of B50 to B100, the combustion was earlier than that of conventional diesel and lower blends, which may likely be due to the higher cetane number.

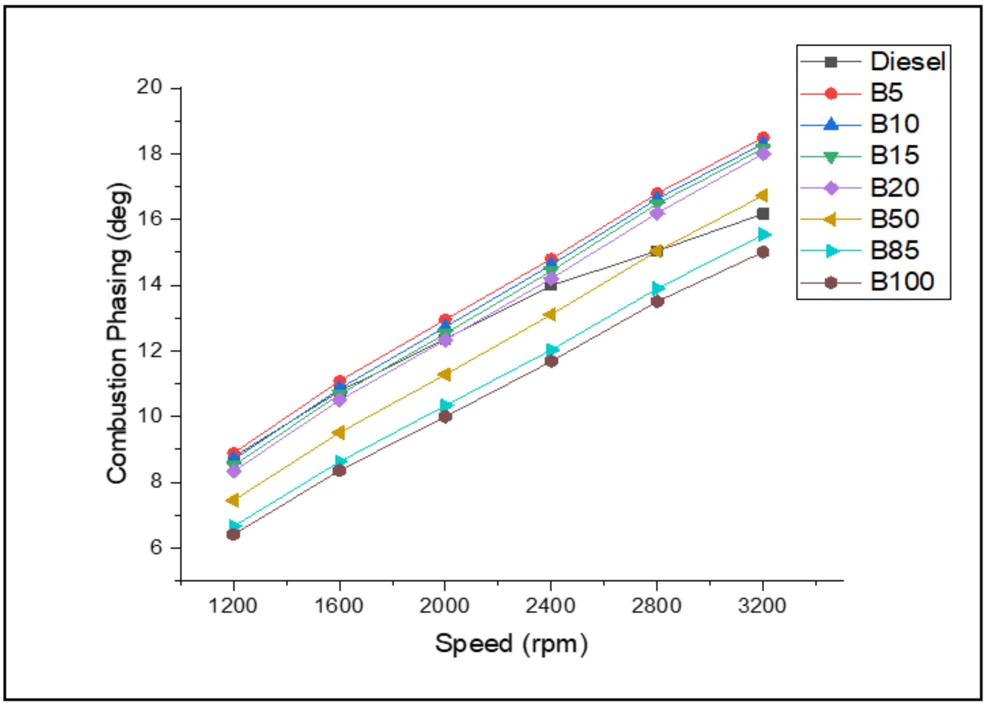

Figure 7 Variation of Combustion Phasing with respect to Speed.

4.2.4 Combustion Duration (CA 10-90)

Combustion duration in an engine is the period during which 10% to 90% of the fuel energy of combustion is released. During this period the combustion is mainly turbulent due to turbulence in the engine cylinder. Figure 8 shows that the combustion duration reduces with an increase in biodiesel blend ratio compared to diesel fuel because of the higher oxygen content which enhances combustion thereby leading to increased combustion duration. Several studies show that biodiesel has a shorter combustion duration than conventional diesel [32]. But all the blends and pure diesel display the same characteristics of increasing combustion duration with an increase in speed which is good as there will be enough time for combustion to take place with reduced emissions.

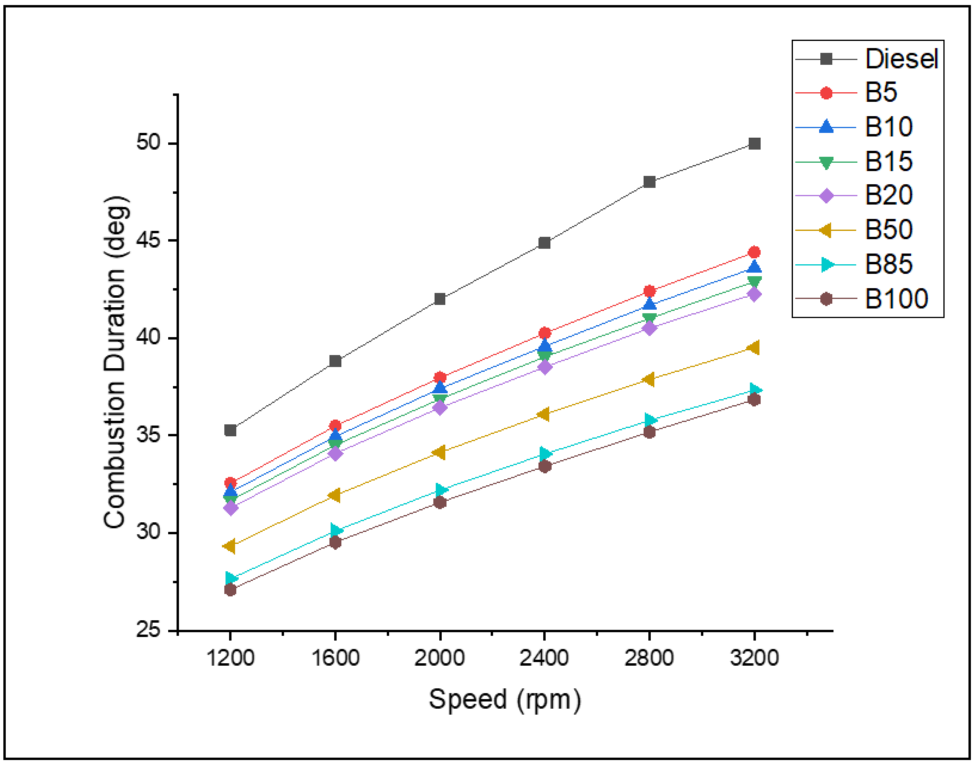

Figure 8 Variation of Combustion duration with respect to Speed.

4.2.5 Mass of Fuel Burned

Figure 9 shows that the fuel mass fraction burned increases with an increase in the biodiesel blend ratio compared to diesel fuel. This increase is because of the higher oxygen content and lower heating value of biodiesel blends.

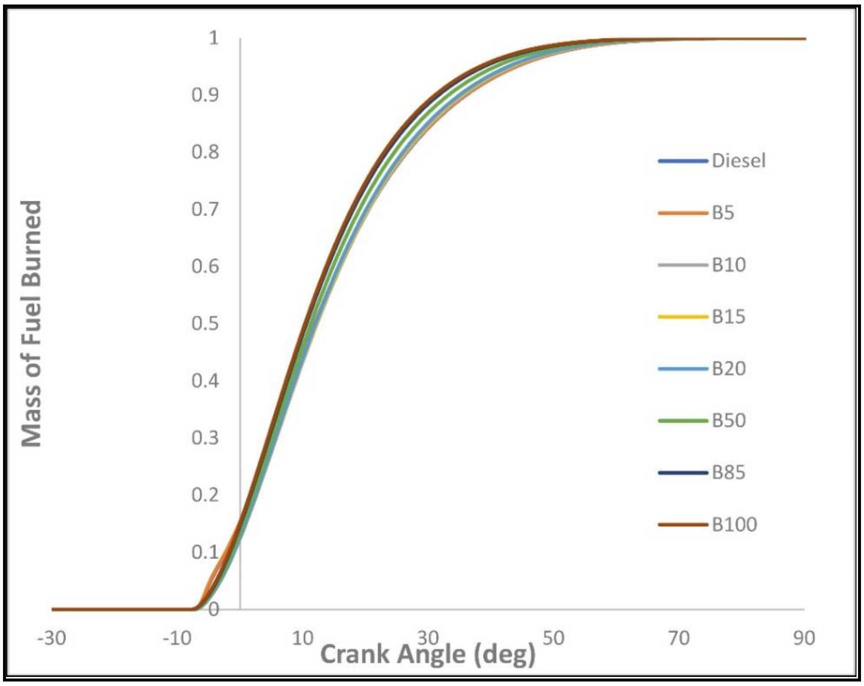

Figure 9 Variation of Mass of fuel burned with respect to Speed.

4.2.6 Heat Release Rate (HRR)

The HRR is the rate at which combustion releases energy. The heat release rate comprises the last three combustion phases: premixed, controlled, and late combustion. The changes in HRR shown in Figure 10, indicates that biodiesel produces lower HRR than diesel because of its higher viscosity, lower calorific value, and shorter Ignition delay and this is in agreement with previous work of other researchers [31, 33].

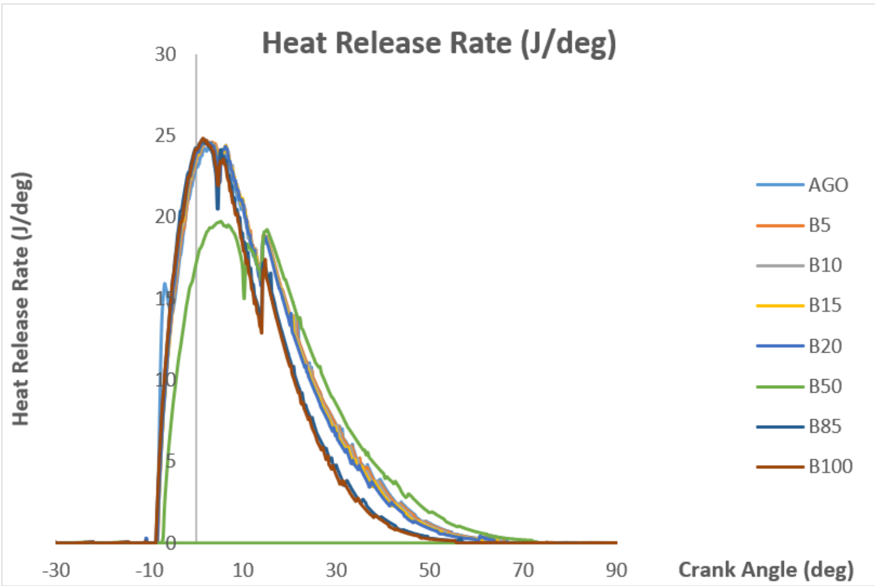

Figure 10 Variation of Heat Release Rate with respect to Speed.

4.3 Emission Analysis

4.3.1 CO Emission

The CO emission decreased significantly with biodiesel blends by 1%, 10%, 15%, 22%, 48%, 68% and 74% with B5, B10, B15, B20, B50, B85 and B100 respectively at 1600 rpm when compared to diesel fuel. It was observed in Figure 11 that as the percentages of the blend increase the CO emissions decrease. This could be attributed to the higher oxygen content of biodiesel than diesel fuel. Higher oxygen content produces a better air-fuel mixing process, thus improving the combustion of the fuel [15]. As the engine speed increases, lower blends of B5, B10, and B15 produced higher CO emission. However, B50, B85 and B100 produced the lowest CO emission at all operational engine speeds used due to their higher oxygen content. Jalaludin et al. [34] stated that more biodiesel in blends produces reduced CO emissions. In comparison, CO emission shows that CO emission increases as speed increases whereas Atabani [24] shows that CO emission reduces with an increase in speed.

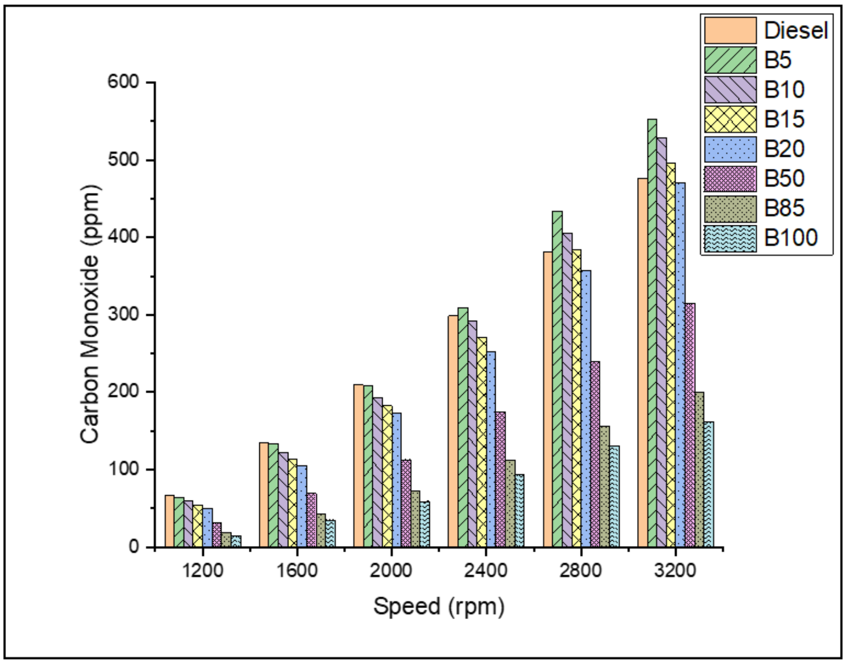

Figure 11 Variation of CO with respect to Speed.

4.3.2 Unburnt Hydrocarbons

Unburnt hydrocarbons are emissions due to incomplete fuel combustion, which depends on the fuel quality, engine design and control system [35]. Figure 12 indicates a similar trend in HC emissions at all operational speeds, but the HC emission from the blends was lower than diesel fuel. At 3200 rpm HC emission for diesel fuel of 49.5394 ppm decreases to 42.8056 ppm with B100. This reduction is because of the higher cetane number of biodiesel blends which produces complete combustion. A linear reduction in HC is observed with the increase in the biodiesel blend ratio. Atabani [24] reported HC reduction with biodiesel blends. However, he only considered two ratios of 10% and 20% biodiesel blend respectively, but studying a wide range of 5% to 100% biodiesel gives a better perspective of the effectiveness of biodiesel in HC emission reduction.

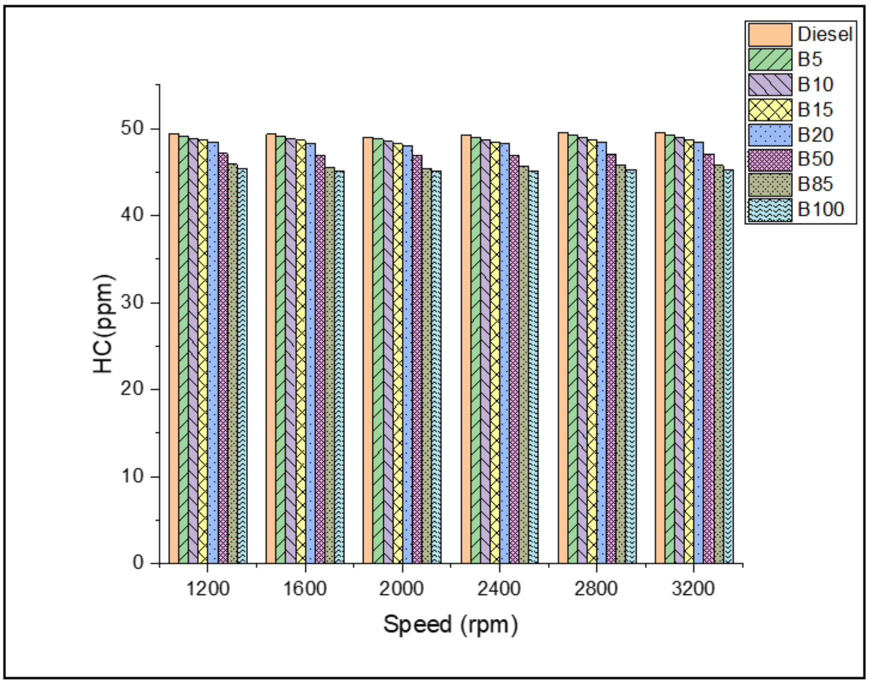

Figure 12 Variation of HC with respect to Speed.

4.3.3 Oxides of Nitrogen

Figure 13 shows the variation of NO_x emission using diesel and biodiesel blends. B10, B15, B20, and B50 produces slightly higher NO_x emission as compared to diesel fuel at all speed levels while B5, B85 and B100 produce lower NO_x emission. [36] also observed a slight decrease in NO_x when waste cooking oil is blended with diesel fuel. In contrast to NO emission generated by Atabani [24], biodiesel blends results of NO_x from 2000 rpm decreases when compared to diesel fuel, which is desirable. [37] Note that decreases in NOx could be associated with low speed and medium speed which produces relatively weak air swirl movement and affects the in-cylinder thermal condition.

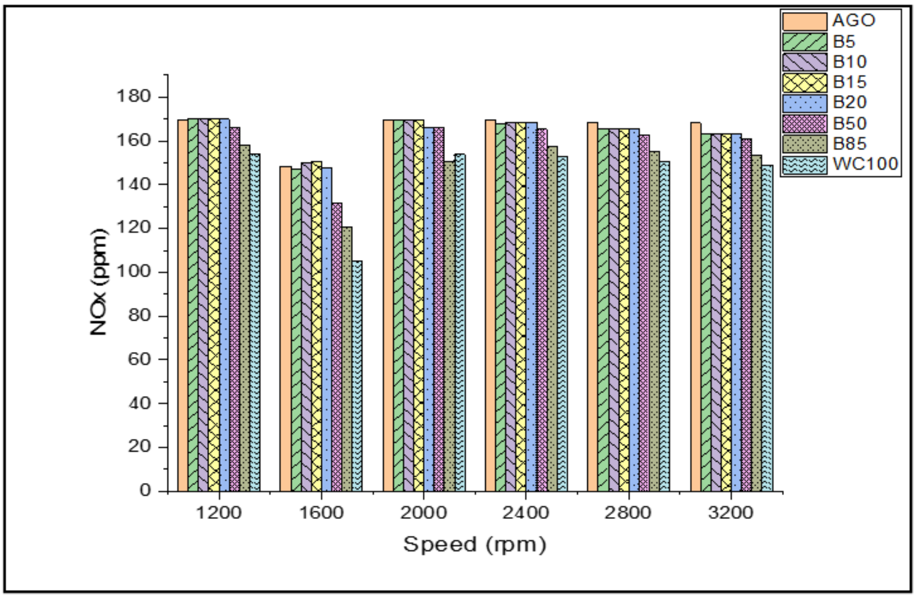

Figure 13 Variation of NO_x with respect to Speed.

Similarly, [38] observed a 1.47% decrease in NO_x emission with used frying oil biodiesel. This was because of the adiabatic flame temperature.

4.3.4 Exhaust Gas Temperature (EGT)

EGT variation shown in Figure 14 presents a decrease in EGT with an increase in biodiesel blend ratio from 1200 rpm to 1600 rpm whereas B5, B10 EGT levels showed an upward trend of diesel fuel from 2400 to 3200 rpm. This phenomenon could be attributed to the lower heat release rate of blends which leads to lower exhaust temperatures [39].

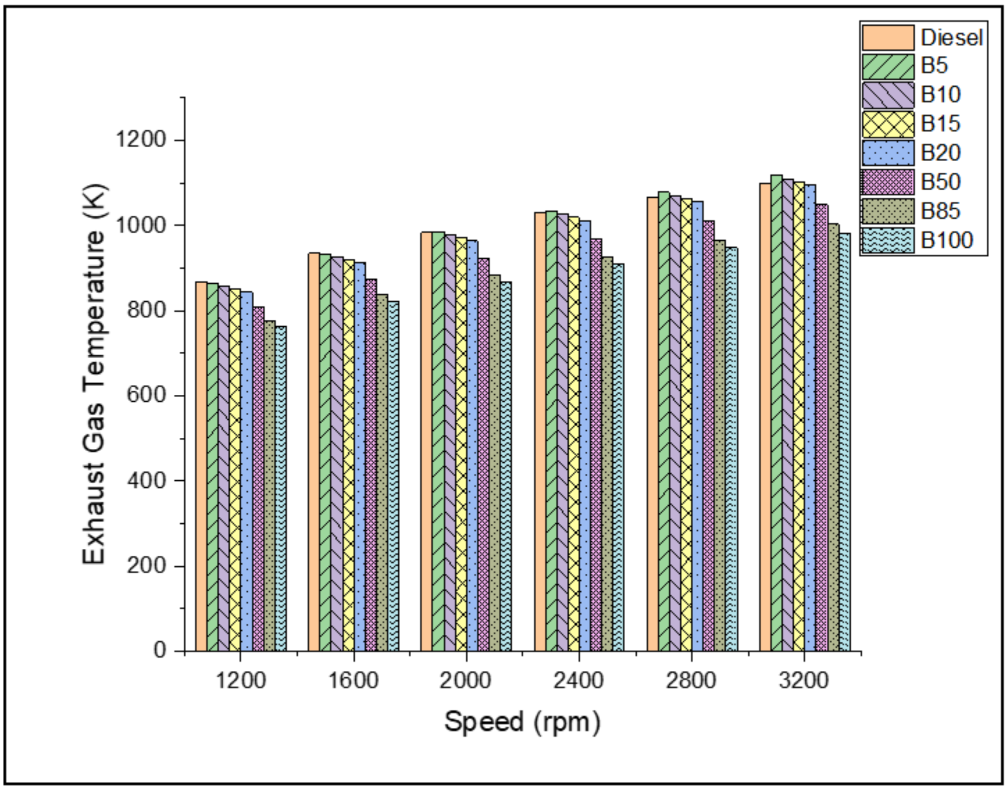

Figure 14 Variation of Exhaust gas temperature with respect to Speed.

5. Conclusion

The simulation of a diesel engine to analyze the performance, combustion, and emission of biodiesel blends and diesel fuel characteristics has been carried out. The following conclusion has been highlighted.

- WCO biodiesel blends at 1200 rpm produce BSFC of, 0.240109 kg/kWhr, 0.241996 kg/kWhr, 0.244331 kg/kWhr, 0.24661 kg/kWhr, 0.26089 kg/kWhr, 0.27947 kg/kWhr and 0.28798 kg/kWhr for B5, B10, B15, B20, B50, B85 and B100 respectively, as compared to 0.239383 kg/kWhr of diesel fuel while the brake power and torque reduce at full load with varying speed.
- Combustion analysis shows that biodiesel blends produce shorter ignition delay, shorter combustion duration, better combustion phasing, increased mass fuel burned and lower heat release rate than conventional diesel fuel.
- CO and HC emissions were reduced significantly with higher proportions of biodiesel blends than diesel fuel. NO_x emission shows a slight decrease with biodiesel blends compared to

diesel fuel.

This study has shown that biodiesel is a viable alternative to conventional diesel fuel providing enhanced combustion and significantly reducing greenhouse gases. Further research can be done integrating catalytic converters and exhaust gas recirculation.

Author Contributions

AAC was responsible for data collection, model formulation, simulation, result interpretation and first draft manuscript, MMO conceived and supervised the project in particular the Positive Valve Overlap concept and the Ricardo Wave, reviewed models and proof read manuscript, OED co-supervised the project, reviewed models and proof read final manuscript.

Competing Interests

The authors have declared that no conflict of interests exist.

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