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Umeuzuegbu JC
Department of Chemical Engineering, Chukwuemeka Odumegwu Ojukwu University, Anambra State Nigeria

Onukwuli OD
Department of Chemical Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria.

Nwanekezie MN
Department of Chemical Engineering, Chukwuemeka Odumegwu Ojukwu University, Anambra State Nigeria

Corresponding Author:
Umeuzuegbu JC
Department of Chemical Engineering, Chukwuemeka Odumegwu Ojukwu University, Anambra State Nigeria

Performance evaluation and emission analysis of sesame seed oil biodiesel in compression ignition engine

Umeuzuegbu JC, Onukwuli OD and Nwanekezie MN

Abstract

This research work focused on diesel engine performance evaluation and emission analysis using sesame seed oil fatty acid methyl ester (SSOFAME). SSOFAME was synthesized by the reaction of sesame seed oil (SSO) with sodium hydroxide dissolved in methanol. The fuel properties of SSOFAME was evaluated based on American Standards for Testing of Materials (ASTM) method The engine performance evaluation of the sesame seed oil biodiesel and the blends B0, B20, B40, B60, B80 and B100 was carried out on Perkin 4:108 diesel engines to evaluate the engine performance characteristics of the fuel, T, BSFC, BTE and BP at varying speed. The trends of the plot of the performance characteristics with engine speed and brake power depicts the engine performance of the SSOFAME and the blends The engine emission analysis was carried out at varying loads using portable digital gas analyzer and a thermometer to obtain the GAS emission characteristics, EGT, CO, HC, and NOx. The plot of emission characteristics of the fuel with engine load shows the extent of emission compared to diesel. The fuel properties of the produced SSOFAME are density 850 kgm^{-3}, kinematic viscosity 4.72 mm^2/s, cetane number 59, flash point 170 °C, cloud point 2 °C, water and sediments 0.02%, acid value 0.25 mgKOH/g, calorific value 38.5 MJ/kg, iodine value 78.2gI$_2$/100 g, pour point 0.5 °C, specific gravity 0.85, free fatty acid 0.13%, and refractive index 1.467. The results of the engine performance evaluation revealed that the engine performance characteristics, T, BTE, BP increased with increase in engine speed and peaked at an optimum speed of 160 rpm for B0 and B20 and 190 rpm for B40-B100 when it start declining with engine speed. The BSFC decrease with increase in engine speed and reached a minimum value at the speed of 160 rpm or 190 rpm as the case may be when it starts to increase with engine speed. B0 exhibit high, T, BTE and BP but lower BSFC compares to SSOFAME and the blends The lower the biodiesel fraction in the blend, the closer the engine performance characteristics approximate that of diesel fuel The results of emission test revealed that the CO, NOx, HC, and EGT increased with increase in engine load. Again the test shows that CO and HC decreased with increase in biodiesel fraction in the blend while NOx and EGT increased with increase in biodiesel fraction.

Keywords: Engine load, brake power, brake specific fuel consumption, engine performance characteristics, sesame seed oil fatty acid methyl ester

Introduction

Biodiesel has now gained tremendous recognition as the alternative to diesel fuel as a result of the problems associated with fossil fuel including, rapid depletion and environmental impact. Biodiesel as an alternative fuel to petro-diesel is renewable, sustainable, environmentally friendly, nontoxic, economically competitive and easily available [1-5]. Biodiesel exhibit some superior characteristics to petro-diesel such as being degradable, higher lubricity, higher cetane number, higher flash point, more oxygen content. However biodiesel is knocked by its higher viscosity, higher cloud and pour point, lower calorific value and lower oxidation stability. Several research works have been carried out on the engine performance and emission characteristics of biodiesel-diesel blend in CI engine [6-12]. A mono-alkyl ester of long chain fatty acid, biodiesel is produced by various methods including, micro-emulsion with alcohol, catalytic cracking, pyrolysis and transesterification [13-15]. However transesterification has been the production method of choice as it is a means of converting oil or fat into environmentally safe biodiesel [16, 17]. Diesel engine are prime movers in the transportation, power generation and construction industries. As a biofuel of choice in compression ignition engine, its performance and emission characteristics need be analyzed before fueling. This research work focused on engine performance and emission analysis of sesame seed oil biodiesel in compression ignition engine. Diesel engine performance and emission analysis were determined by evaluating and making comparative plots of the engine performance and emission characteristics of biodiesel and blends, torque (T), brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust gas temperature (EGT), engine emissions, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx) with those of diesel. Although extensive research have been conducted on the engine performance and emission characteristics using different feedstock, the use of sesame seed oil has not been so extensively researched upon, hence the choice of sesame seed oil biodiesel.

2 Materials and Methods

2.1 Materials

Sesame seeds, reagents, glass wares, equipments including hot plates, gas chromatography mass spectrometer (GC-MS), Fourier transform infrared spectroscopy (FTIR), viscometer, soxhlet extractor, specific gravity bottles; electrostatic oven etc.

2.2 Experimental Methods

2.2.1 Sample preparation

The sesame seeds used in this research work was bought from Ogbete market Enugu, Enugu state, Nigeria. 10 kg of the sesame seeds was sorted and washed with water to remove sand, dirt and other impurities. The seed was then dried and de-shelled manually. The de-shelled seed was sundried for three days and further oven-dried at temperature of 50 °C for 3 days in other to eliminate the moisture content and then size-reduced by grinding with mechanical grinder. The sample was then kept for further analysis.

2.2.2 Extraction of oil from sesame seed

Sesame seed oil content was determined from 18 hours of soxhlet apparatus extraction using n-hexane solvent. The use of n-hexane solvent is in agreement with the finding of [18-22] who reported enhancement of oil yield from sesame seed using n-hexane. The bulk of oil used in this work was as well hexane-solvent extracted. 3kg of the dried, ground sesame seed was measured into a plastic container containing 3 liters of n-hexane. The mixed content of the container was vigorously shaken after covering the container. The container was made air tight to prevent evaporation of the solvent and then kept to macerate the seed for a day. Then the dissolved oil in n-hexane was decanted and the slurry filtered. The filtrate was distilled to recover the solvent at 65 °C [23]. The percentage oil content was calculated as:

$$\% \text{ oil yield} = \text{weight of oil obtaind} \div \text{weight of seed sample} \times 100 \qquad (2.1)$$

2.3 Production of SSOFAME

The free fatty acid and moisture content of sesame seed oil, which are in excess of 1% respectively was pretreated with concentrated sulphuric acid and methanol to reduce their respective value below 1.0% before being transesterified with sodium hydroxide catalyst. The biodiesel in this work was produced using the normal laboratory method of preparation. A side arm of the three-necked round bottomed flask used as the reactor, was fitted with a thermometer while the central arm was fitted with a condenser (plate 1). The amount of oil specified for the reaction was run into the flask and the oil heated to the specified temperature for the reaction. Specified amount of sodium hydroxide solution in methanol was added onto the flask content. The hot plate stirrer was switched on after setting the stirrer speed at the value required for the reaction. Heating was continued and the flask content continuously stirred and refluxed. At the end of transesterification, the flask content was poured into separating funnels, allowed to settle for a day where it separated into upper biodiesel layer and the lower glycerol layer. The two layers were tapped off separately, the glycerol layer first followed by the biodiesel layer. As the biodiesel layer may contain some traces of sodium hydroxide and glycerol, they were removed by wet washing. The washed biodiesel was then dried on a laboratory hot plate at 105 °C to remove all traces of moisture remaining in it. The percentage biodiesel yield is given by the expression,

$$\% \text{ biodiesel yield} = \text{Volume of biodiesel produced} \div \text{volume of oil used} \times 100 \qquad (2)$$

2.4. Determination of the fuel properties of SSOFAME

The fuel properties of the sesame seed oil biodiesel produced were characterized based on ASTM method. The properties characterized include density, viscosity, iodine value, saponification value, cetane number acid value, free fatty acid, calorific value, flash point, cloud point, pour point etc.

2.5 Engine performance evaluation test

The engine performance evaluation test of the SSOFAME was carried out on a Perkins 4:108 diesel engines mounted on a steady state engine test bed as shown in plate 2. The engine is a four cylinder, water-cooled, naturally aspirated, 4-stroke CI engine. The engine specification is as given in Table 1. The experiment was conducted with no. 2 diesel fuel, SSOFAME and their blends. The blends by volumes are, 0% biodiesel (B0), 20% biodiesel (B20), 40% biodiesel (B40), 60% biodiesel (B60), 80% biodiesel (B80), and 100% biodiesel (B100). B0 and B100 are neat diesel and biodiesel respectively. A short test run was done in order to ensure that all essential accessories were in working order before the actual test.

2.5.1 Engine test at varying speed

In carrying out this test, the engine was started after running into the fuel chamber 100 cm^3 of the fuel blend under test and the engine kept at maximum load of 100 kg. The engine speed in rpm was measured using tachometer attached with the dynamometer and kept at a relatively low speed of 1000 rpm and then the value of the torque was taken and recorded. The time taken for the 100 cm^3 of the fuel used to be consumed at this speed was noted using stop watch. The manometer reading was taken, as well as the reading of exhaust gas temperature. The above procedure was repeated for higher speed values of 1300 rpm, 1600 rpm, 1900 rpm and 2200 rpm.

2.5.2 Engine emission test at varying load

For this test, the engine was started after running into the fuel chamber 100 cm^3 of the fuel blend under test and the engine kept at a constant speed of 1900 rpm, and loaded 20 kg. The exhaust gases, NOx, CO, and HC were measured with a portable digital gas analyzer (Testo XL 450). The data of exhaust emissions were taken from the end of the exhaust pipe of the engine. After taking the necessary readings including exhaust gas temperature (EGT) at this specified load, the load on the engine was varied using the dynamometer loading wheel. The procedure was repeated for higher loads 40 kg, 60 kg, 80 kg and 100 kg.

Plate 1: Biodiesel production by transesterification of oil

Plate 2: Perkin 4:108 diesel engine mounted on Steady state engine test bed at UNN Nsuka

Table 1: Engine specifications

Components	Values
Engine	
Type	Perkins 4:108
Bore	79.735 mm
Stroke	88.9 mm
Swept volume	1.76litres/cycle
Compression ratio	22:1
Maximum BHP	38
Maximum speed	3000 rpm
Number of cylinder head	4
Diameter of exhaust	1½"
Length of exhaust pipe	36”31’
Dynamometer	
Capacity	112kw/150hp
Maximum speed	7500 rpm
KW	(Nx rev/min)/9549.305
Fuel guage	
Capacity	50-100 cc
AIR BOX	
Orifice size	58.86 mm
Coefficient of discharge	0.6

Source: Department of Mechanical Engineering, University of Nigeria Nsuka

3 Results and Discussion

3.1. Fuel Properties of the SSOFAME Produced.

The summary of fuel properties of SSOFAME produced is as given in table 2. From the data in the table, it could be discerned that SSOFAME has properties similar to those of the diesel and therefore could be blended in the right proportion to obtain fuel suitable for use in compression ignition (CI) engine without modification of the engine. Density is very important property in the metering of fuel as the fuel is measured volumetrically. Fuel’s viscosity determines its degree of atomization in a CI engine. The experimentally determined values of density and viscosity of sesame seed oil biodiesel produced are 850 kg/m^3 and 4.72 mm^2/s respectively. The density and viscosity of SSOFAME are lower than that of SSO from which it was produced. High density and viscosity of fuel results in poor atomization in compression ignition engine, which gives rise to carbon deposits, plugging of fuel filter and injector cocking [24] therefore reducing the engine power output. The essence of transesterification is to reduce the density and viscosity of oil in order to circumvent the above-mentioned problems. However the viscosity of fuel should not be excessively low as this produced very subtle spray which cannot properly get into the combustion cylinder, thus forming a fuel rich zone that give rise to formation of sooth [24, 25]. The flash point is a determinant for flammability classification of materials. The typical flash point of pure methyl ester is ≥130 °C, classifying them as “non-flammable”. However, during production and purification of biodiesel, not all the methanol, might be removed, making the fuel flammable and dangerous to handle and store if the flash point falls below 130 °C. The experimentally determined flash point of the SSOFAME is 170 °C. This falls within the ASTM standard as shown in table 4, indicative of its safety in handling and storage.

Cetane number which serves as a measure of ignition quality of a fuel was experimentally determined as 59 for SSOFAME. Fuels of low cetane number shows increase in emission due to incomplete combustion. The ASTM limit for biodiesel cetane number is 147. Thus the evaluated cetane number of 59 for SSOFAME is within the ASTM standard, indicative of the fact that the produced biodiesel possess good ignition response. A good quality biodiesel is expected to be of low acid value as high acidic content may corrode and damage machine parts. The acid value of SSOFAME in this work is determined as 0.25 mgKOH/g. which is within the ASTM limit. Low saponification number is expected of high quality biodiesel as oil of high saponification value is prone to soap formation with alkali catalyst and thus reduction of quality and quantity of the biodiesel produced.

The cloud point which is the lowest temperature of first appearance of wax-like material on cooling the biodiesel was determined as 2 °C for SSOFAME while the pour point which is the lowest temperature at which the fuel will still pour was determined as 0.5 °C. The cloud and pour points are moderately low but not sufficiently that it might not give rise to cold flow problems in cold season especially in the cold regions. This cold flow problem however could be overcome by the addition of suitable cloud and pour point depressants or by blending with diesel oil [24]. The properties of the biodiesel produced are within the ASTM limit for biodiesel, as shown in table 2.

Table 2: Fuel properties of SSOFAME

Properties	Unit	SSOFAME	ASTM Standards	Test method
Density	Kgm^{-3}	850	860-900	D93
Kinematic viscosity	mm^2s^{-1}	4.72	1.9-6.0	D445
Cetane number		59.0	47 min.	D613
Flash point	°C	170	100 to 170	D93
Cloud point	°C	2	-3 to -15	D2500
Water &sediment	%	0.02	0.05	D2709
Acid value	$mgKOHg^{-1}$	0.25	0.50	D664
Calorific value	$MJKg^{-1}$	38.5	42.06	D35
Iodine value	gI_2/100 g oil	86.4	42-166	
Pour point	°C	0.5	-10 min.	D97
Specific gravity		0.85	-	D287
Free fatty acid	%	0.13	-	
Refractive index		1.467		

3.4 Engine performance evaluation of diesel, SSOFAME and the blends

The engine performance evaluation characteristics namely, torque (T), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and brake power (BP) were computed using the formulae shown below. The engine performance evaluation characteristics were plotted against engine speed for the biodiesel, diesel and the blends. The plots for the biodiesel and the blends against engine speed were compared with that of the diesel against speed in order to evaluate the performance and suitability of the biodiesel and the blends as a suitable compression ignition engine fuel.

3.4.1 Calculations of engine performance evaluation characteristics

Volume flow rate of fuel, V_f (m^3/s) =V/t

Where V= volume of fuel (m^3) and t = time(s)

i) Mass flow rate of fuel M_f,(kg/s) = $\rho_f V_f$

ii) Brake power, BP (KW) = TxN/9549.30

iii) Where T=torque (Nm), N =engine speed (rpm), ρ_f = density of fuel (Kg/m^3)

iv) Brake thermal efficiency, BTE (n_{BT}) (%) = BP/M_f x44200

v) Brake specific fuel consumption, BSFC (Kg/KWh) = 3600 M_f/BP

3.4.2 Effect of engine speed on Torque for diesel, SSOFAME and the blends

Figure 1 shows the plot of variation of engine torque with engine speed for diesel, SSOFAME and their blends at full load. The engine torque increased with increase in engine speed until a maximum value was attained at an optimum speed of 1600 for diesel and at 1900 for SSOFAME when the torque starts to decrease. The decrease in torque noticed on exceeding the optimum speed results from the fact that at such a high speed, the temperature of the fuel increased which culminated in the reduction of the viscosity and lubricity of the fual and hence reduction of the engine torque. Diesel exhibitt higher torque compared to biodiesel and blends as a result of its higher energy content in addition to the high viscosity and density of biodiesel and blends which predisposed reduction of engine power. The variation of speed in the attainment of maximum torque between diesel and biodiesel with blend stem from their energy content differences. Again, at a specific engine speed, torque increased with decrease of biodiesel fraction in the blend. This is in conformity with the findings of [26-30] who reported a drop of engine torque due to less heating value of biodiesel.

3.4.3 Effect of engine speed on brake specific fuel consumption (BSFC) for diesel, SSOFAME and the blends

Low BSFC of an engine indicate that the engine use less amount of fuel to produce equal amount of work as another rated higher, and as such low BSFC is preferred to higher one. Figure 2 depict the effect of engine speed on BSFC. From the Figure, it could be observed that BSFC decreased with increase in engine speed and attained minimum value at an engine speed of 1600 rpm for B0 and B20 and 1900 rpm for B40-B100 and then increased with increase in speed. The decrease of BSFC with engine speed could be attributed to the fact that initially, the engine speed was relatively low and therefore the engine and fuel temperatures were low and as such the viscosity and lubricity were stably high resulting to high torque and thermal efficiency of the engine. The later increase in BSFC with engine speed stems from the fact that at higher speed, the engine and fuel temperature soared resulting in the reduction of the viscosity and lubricity of the fuel. Consequently, the torque and thermal efficiency of the engine decreases resting in higher BSFC. Again from Figure 2, it could be observed that at specific engine speed, the BSFC increased with increase in biodiesel fraction in the blend. This agrees with the findings of [31-36], who reported that fuel consumption of an engine fueled with biodiesel is higher as more of the fuel is required to compensate for the low heating value of biodiesel.

3.4.4 Effect of engine speed on brake thermal efficiency for diesel, SSOFAME and blends

Figure 3 shows the effect of engine speed on brake thermal efficiency of a diesel engine fueled with diesel, SSOFAME and the blends. From the Figure it could be seen that BTE increased with increase in engine speed at full load and peaked at optimum speed of 1600 rpm for B0 and B20 and 1900 rpm for B40-B100 and then decreased with increase in speed. BTE increased with engine speed initially because increase in speed resulted to increased torque and hence the thermal efficiency of the engine. At higher speed in excess of the optimum more amount of fuel is injected into the combustion cylinder per cycle. As a result of the high engine speed, the fuel will not have sufficient time for complete combustion resulting to reduction of the engine efficiency [37]. Figure 3 also revealed that the thermal efficiency of B0 and B20 are very close. This could be as a result of closeness of their heating values. Again, at specific engine speed, brake thermal efficiency decreased with increase in biodiesel fraction in the blends ostensibly as a result of low calorific value of biodiesel compared to diesel.

3.4.5 Effect of engine speed on brake power for diesel, SSOFAME and blends

The variation of brake power with engine speed for SSOFAME, biodiesel and the blends are as shown in figure 4. It could be seen from the Figure that the BP of diesel, SSOFAME and the blends increased with increase in engine speed and attained maximum value at an optimum speed of 1900 rpm for B0-B100 from where it then decreased with increase in engine speed. The increase in BP with engine speed initially observed before peaking at 1900 rpm optimum speed resulted because the initial relatively lower speed steadily enhanced the lubricity of the fuel with resultant high torque. At higher speed in excess of 1900 rpm, the torque as well as the lubricity of the fuel reduced with increase in speed resulting in the reduction of engine BP. This is in agreement with the findings of [38-43], who reported that engine power decreased with increase in biodiesel fraction in the blend.

3.4.6 Variation of brake specific fuel consumption with brake power for diesel, SSOFAME and blends

Variation BSFC with BP is as shown in figure 5. From the figure, it could be observed that BSFC decreased with increase in BP and then attained minimum value. At a specific brake power, the BSFC increased with increase in biodiesel fraction. This could result from the fact that the heating value of diesel exceeds that of the biodiesel [32-34].

3.4.7 Variation of brake thermal efficiency with brake power for diesel, SSOFAME and blends

The effect of brake power on brake thermal efficiency is shown in figure 6. From the figure, it is discernible that as the brake power increases, the break thermal efficiency increased. From the figure, it is that at a definite brake power, the brake thermal efficiency decreased with increase in biodiesel fraction, and thus B0 exhibit the highest BTE followed by B20.

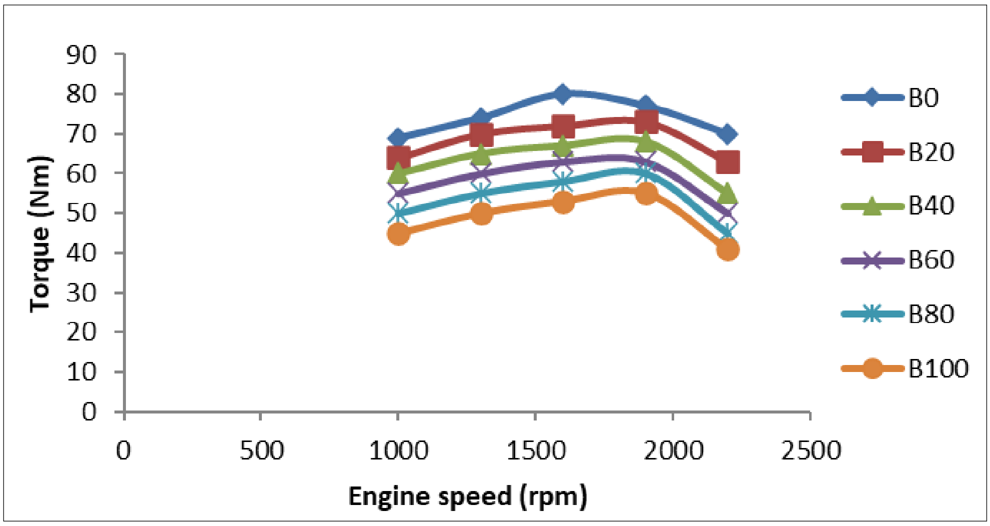

Figure 1: Variation of torque with engine speed for different biodiesel fraction

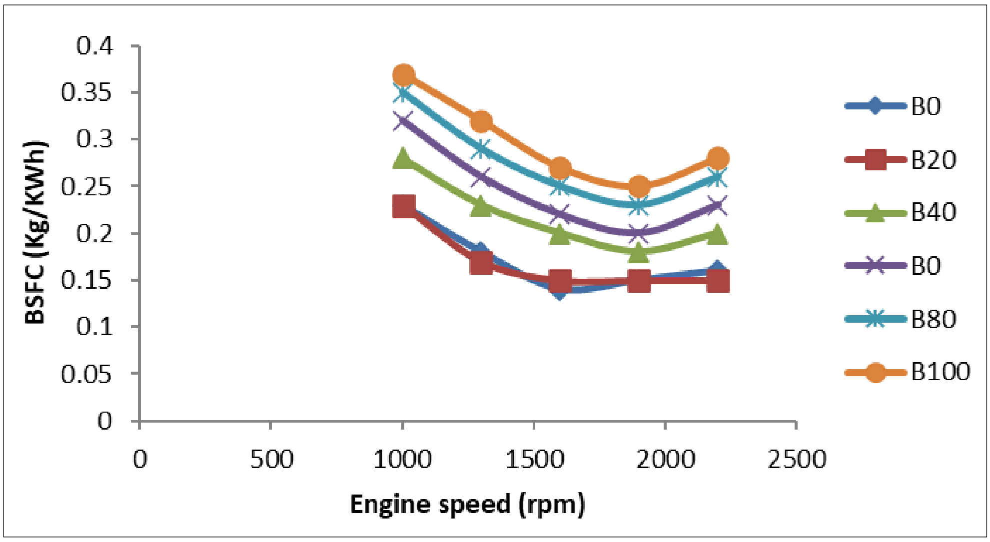

Fig 2: Variation of BSFC with engine speed for different biodiesel fractions

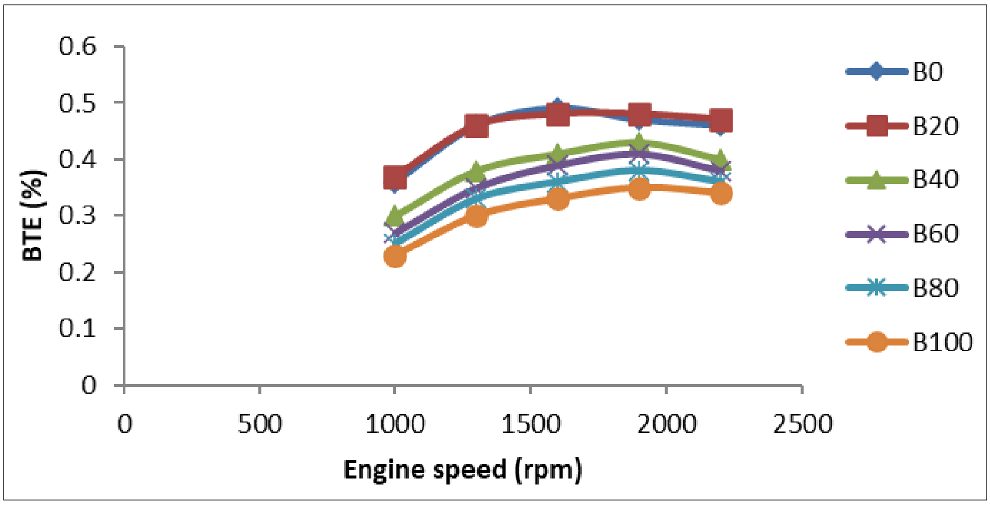

Fig 3: Variation of BTE with engine speed for different biodiesel fraction

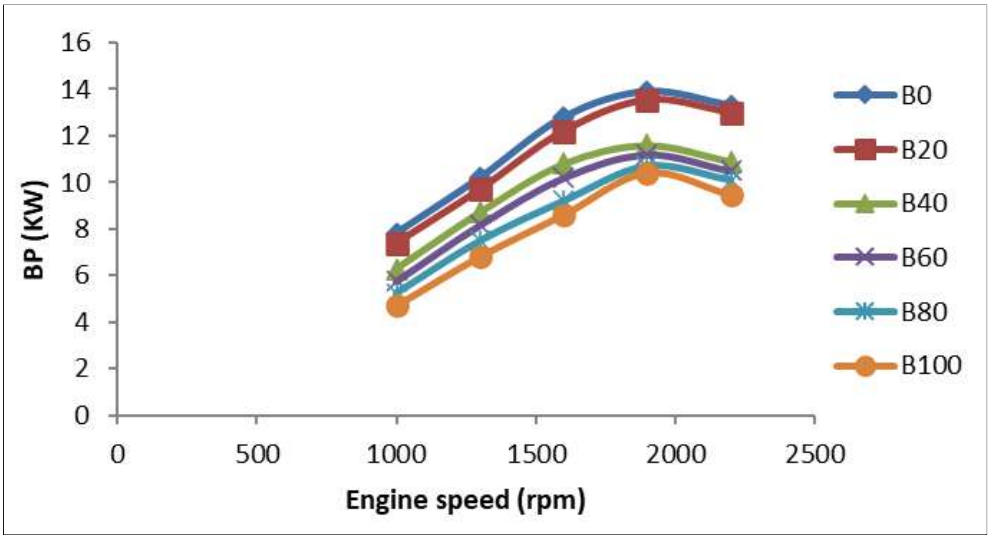

Figure 4: Variation of BP with engine speed for different biodiesel fraction

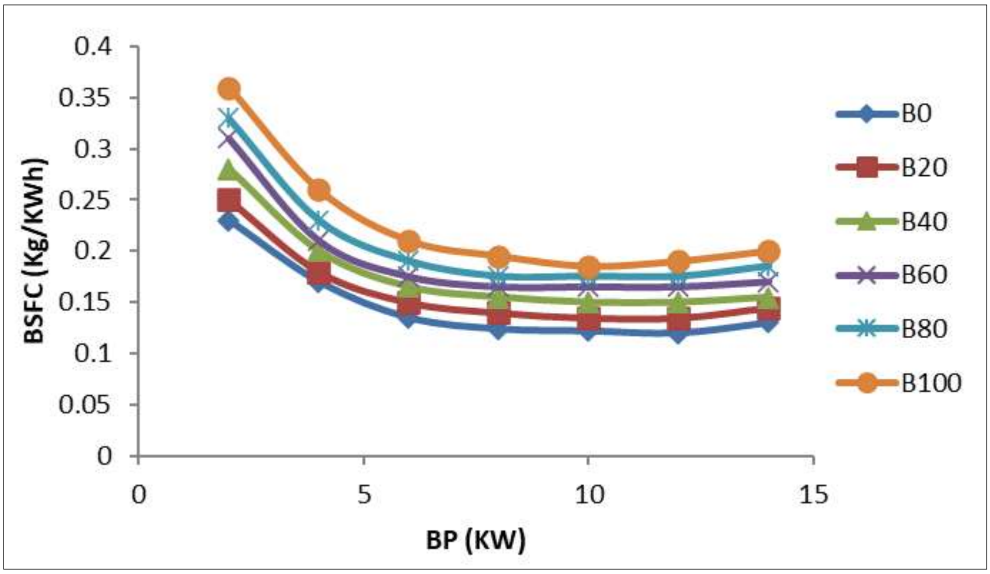

Fig 5: Variation of BSFC with brake power for different biodiesel fraction

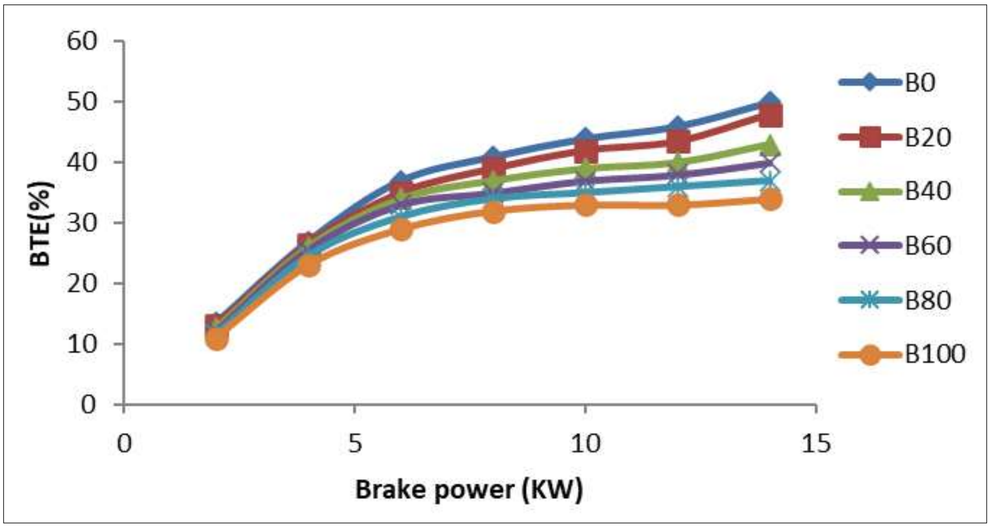

Fig 6: Variation of BTE with BP for different biodiesel fractions

3.5 Engine emission analysis for diesel, SSOFAME and blends

3.5.1 Effect of engine load on exhaust gas temperature

Exhaust gas temperature, EGT, indicate the rate of heat released during combustion of a fuel. The effect of heat load on EGT is as shown in Figure 7. From the figure it could be observed that increase in engine load result in increase of EGT. The oxygen content of biodiesel which improves its degree of combustion result in its enhanced temperature. This finding conformed with those of [44, 45], who reported increase of EGT with increase in load in diesel engine for mahua and jatropher biodiesels respectively. Again from the figure it is discernible that at a specific load, EGT decreased with increase of biodiesel fraction in the blend.

3.5.2 Effect of engine load on CO, HC and NOx emission for diesel, SSOFAME and blends

3.5.2.1 Effect of engine load on CO and HC emission of diesel, SSOFAME and the blends

Figures 8 and 9 showed the effect of engine load on CO and HC emission respectively for diesel, SSOFAME and the blends. From the figures it could be observed that CO and HC emission increased with increase in engine load. The increase in emission as a result of increase in load could be explained from decreased air-fuel ratio resulting from increase in load which gave rise to incomplete burning of the fuels. From figures 8 and 9 respectively it could be observed that CO and HC emissions decreased with increase in biodiesel fraction in the blend. This is in agreement with the findings of researchers [46-50], who reported a reduction in CO and HC emission when a diesel engine is fueled with biodiesel instead of diesel. This shows that the use of biodiesel lowers the CO and HC emission. This could be explained from the point of view of oxygen content and low carbon to hydrogen ratio of biodiesel. The oxygen content of biodiesel increased the vaporization and atomization of biodiesel and hence enhances its complete combustion leaving low amount of CO and HC in the combustion product as compared to diesel fuel [51-55]. The low carbon to hydrogen content of biodiesel compared to diesel presents less carbon to be burnt which translates to low CO and HC in the combustion product.

3.5.2.2 Effect of engine load on NOx emission of diesel, SSOFAME and the blends

Figure 10 shows the effect of engine load on NOx emission for the fuels. From the figure it could be observed that NOx emission increased with increase in engine load. This could be explained by the fact that increase in engine load reduce the air-fuel ratio resulting in incomplete combustion of the nitrogen components of the biodiesel, thus emitting the oxides of nitrogen or NOx. From the figure, it is also discernible that at specific engine load, NOx emission increases with increase in biodiesel fraction. This is in conformity with the findings of [56-60].

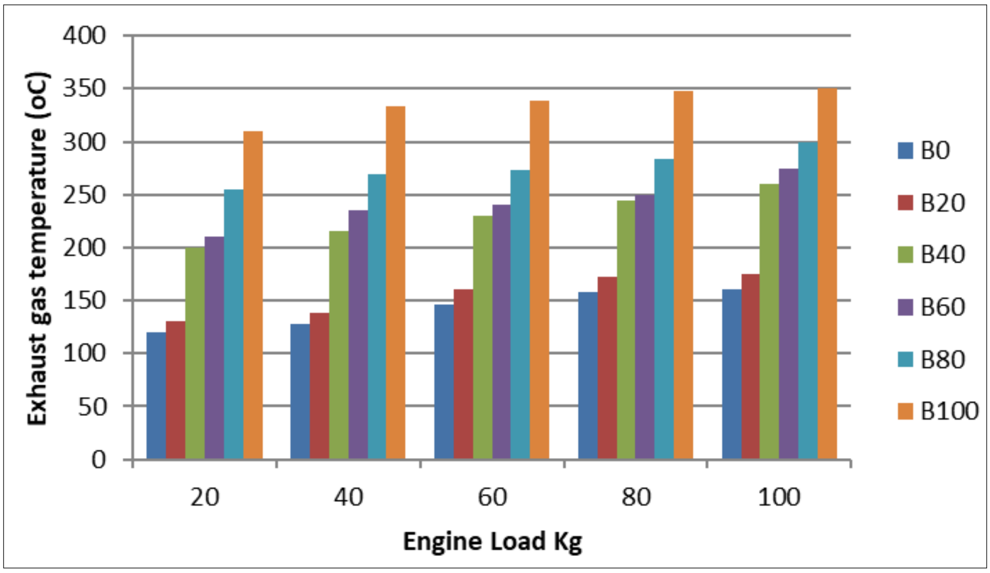

Fig 7: Effect of engine load on exhaust gas emission for diesel, RSOFAME and blends

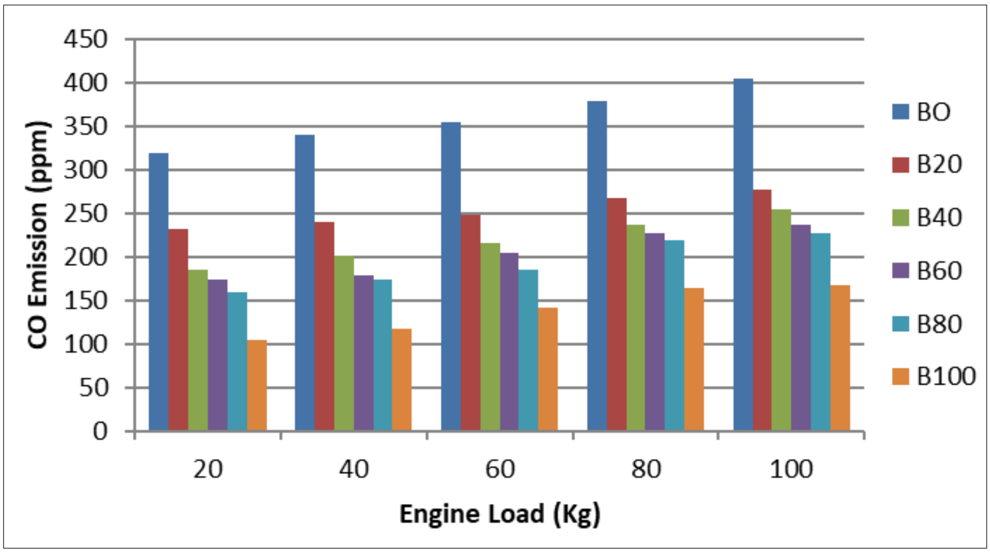

Fig 8: Effect of engine load on CO emission for diesel, RSOFAME and blends

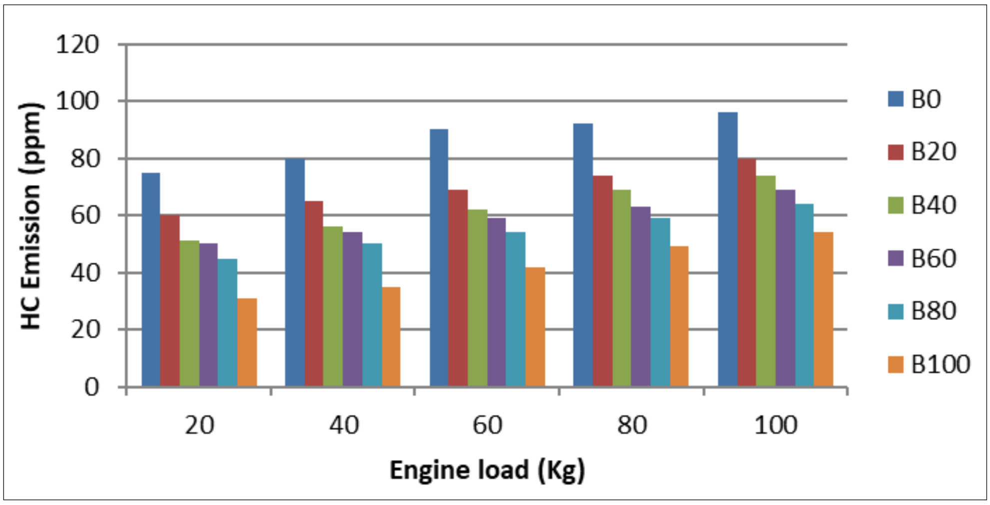

Fig 9: Effect of engine load on HC emission for diesel, RSOFAME and blends

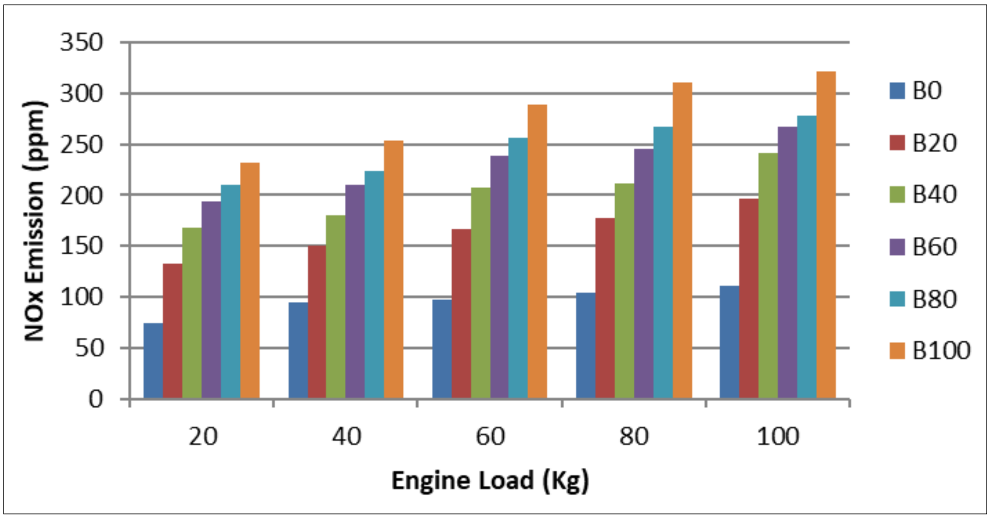

Fig 10: Effect of engine load on NOx emission for diesel, RSOFAME and blends

4. Conclusion

High yield of SSOFAME was achieved by sodium hydroxide catalyzed methanolysis of SSO. Engine performance evaluation of SSOFAME and the blends showed the fuel to be a good substitute to diesel because of the closeness of their engine performance characteristics, T, BSFC, BP and BTE. The engine emission analysis of SSOFAME and the blends showed a reduction in CO and HC emission with less impact in the environment while NOx emission is high with higher impact in the environment.

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