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A Comparative Evaluation of Selected Biodiesel Performance and Specific Emission in Relation to Emission Standard

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Abstract: Biodiesel holds significant promises in addressing the current challenge of alternative energy sources. Pure biodiesel prepared from Jatropha, Moringa and waste restaurant oil was evaluated along with normal diesel in a single-cylinder diesel engine. The performance and emissions were subsequently analyzed in comparison to the Environmental Protection Agency of the United States and the European Commission Standard. The difference in performance and emissions were marginal and mixed. Oxides of Nitrogen production strongly correlated with excess air and temperature as predicted by the Zeldovich mechanism. The various emissions showed some compliance with set limits and highlighted areas of challenges within the test cycle. The undesirable emission trend suggests a largely kinetically driven process, creating scope for novel engine design as a common remediation strategy regardless of the differences in fuel chemistry.

Keywords **:** Pure Biodiesel, Performance, Brake Specific emission, Emission Standards, Zeldovich Mechanism.

1. Introduction

It has been established that diesel engines running on biodiesel or its blends tend to reduce harmful emissions such as carbon monoxide (CO), particulate matter (PM) and total hydro-carbon along with a drop in performance, while at the same time, increasing oxides of nitrogen (NO_X) emission and specific fuel consumption [1, 2]. These mixed pictures, to some degree, have created ambivalence. But the potential capacity of biodiesel to enhance sustainability, broaden energy access and reduce emission remains attractive and given that the current compression ignition (diesel) engine was conceived and designed primarily for hydrocarbon-sourced fuel, emerging scenarios of future fuel type are eclectic and, that ongoing research point to a determined effort to develop a novel engine that can run on fuel type with more diverse chemistry, indicates there exists a niche for biodiesel, particularly those from the non-edible food source.

Exploring this niche requires that all potential sources are exhaustively investigated, performance and emission measurements determined in specific terms and benchmarked with conventional fuel and proposed emission standards. Only then will the extent of mitigation be determined and the plan of action categorized. Pollutant exhaust emission limits have already been set by the United States Environmental Protection Agency (US EPA) and the European Commission (EC) in release documents [3-5]. According to the EC document, the standards are harmonized according to ISO 8178 – 1:1996 [6]. All EU states were required to apply directive 2003/44/EC [7] from 1st January 2005. These measures came into effect on 1st January 2006. The emission measurements for CO, NOx, PM and THC were required to be in Brake-specific format (g/kWh). Rules on test cycle runs were also set to enable emission measurement to be made under steady-state conditions. It is noteworthy that while some work on biodiesel mentioned these pollutant emission standards [8], most did not bench-mark their measurement against the limit set by the regulation [9, 10] and a few did not compute emission based on the brake-specific (g/kWh) format [11].

Against the backdrop of an accelerating rate of urbanization and the consequent proliferation of fast-food culture, the availability of vast margin of land needing reforesting efforts to stem the tide of desertification, and an acute need for safe water and food beneficiation for the rural poor, Sub-Sahara Africa has a clearly defined niche in producing biodiesel from the non-edible source such as waste restaurant oil, Jatropha seed oil and Moringa seed oil. By 2030, Africa's population is expected to peak at 1.5 billion with the percentage of those living in urban areas being 748 million (53.5% of the total) [5, 12]. The promotion of these three sources of biodiesel, in sub-Saharan Africa, apart from limiting greenhouse gas emissions, and enhancing energy sustainability, will promote universal accessto energy sources and even out economic growthbetween resource-rich and poor countries in theregion.

This work involved sourcing, extraction and production of biodiesel from Jatropha, Moringa and waste restaurant oil. The physicochemical properties of the oil/fuel were determined and benchmarked against normal diesel, after which their performance and emission trend were evaluated in an internal combustion diesel engine.A comparative study of the emission against the backdrop of the stipulated regulation was done to highlight test cycle areas of challenge.

2.0 Materials and Methods

2.1 Materials

Seeds of Moringa and Jatropha sourced from the wild in a large area bothering Central and North-Eastern Nigeria were processed appropriately. Oil extraction was achieved via two methods, soaking and Soxhlet. Three solvents were employed for thispurpose to optimize yield. The solvent was petroleum ether, normal hexane (n-hexane) and a wild card, distilled gasoline. The three solvents were used to determine the most efficient means of extraction. This is an important consideration giventhe difference in cost, availability, and solvent recovery rate. For every 150g of pulverized oven-dried sample, 400ml of solvent was used for soaking and 600ml of Soxhlet extraction. The waste oil (yellow grease) biodiesel was processed from used grand cereal oil originally extracted fromsoybeans.

A series of physio-chemical properties of the oil were determined. They include density, viscosity, pour and cloud point, iodine value, refractive index,flash point, free fatty acid (FFA) value, saponification and peroxide. Value details of the extraction yield and oil properties are given in Table1(a) and (b). Trans-esterification was achieved using alkaline catalyst, potassium oxide and methanol for the alcohol component. The resulting biodiesel was processed and tested. The fuel properties are given in Table 1(c).

Table 1: Oil extraction, properties and test rig technical details.

a) Extraction yield

Method	Moringa			Jatropha		
	n-Hexane	Petroleum-ether	Distilled gasoline	n-Hexane	Petroleum-ether	Distilled gasoline
Soxhlet	37.1	24.3	40.2	51.8	25.3	34.1
Manual	13.7	14.1	20.8	26.7	17.7	23.13

b) Experimentally determine the physio-chemical properties of extracted oil.

S/No	Properties	Moringa Oil	Jatropha Oil
1	Viscosity (cS)@30ºC	53.9	41.45

2	Density (kg/m^3)	912.0	890.62
3	Iodine value	64.84	108.40
4	Refractive Index	1.458	1.455
5	Flash point (°C)	215	195
6	Free Fatty Acid	9.96	2.48
7	Saponification Value (mgkOH/gm)	185.15	196.44
8	Peroxide Value	1.84	3.21
9	Pour Point (°C)	8	5
10	Cloud Point (°C)	12	7

c) Fuel properties of biodiesel

Properties	*Moringa biodiesel*	*Jatropha biodiesel*	*Waste oil Biodiesel*	*ASTM D6751-2*
Density (kg/m^3)@30°C	892.9	880.52	897.4	875-900
Viscosity(mm^2/s)@ 30°C	4.65	4.56	4.27	1.9-6.0
Heating value (LHV, kJ/kg)	40.05	39.45	39.4	(diesel-45.84)

c) Technical Specifications of Test Rig Equipment.

Device	Description		Detail
	Engine	Model	TQ: TD 111
	Maximum power (kW)		3.5
	Type		Naturally aspirated, four strokes.
	Rated speed(rpm)		3900
	Number of cylinders		1
	Compression ratio		17.5:1
	Combustion		Direct injection
Hydraulic dynamometer		Model	TQ: TD115
		Type	Hydraulic
	Water pressure		6-12m head of water (60KPa)
	Range		0-14Nm
	Water flow rate		4lt/min
Exhaust gas analyzer		Model	SV-5Q

HC	Range	1-10000	10^{-6} (ppm) Vol.
	Resolution	1 ppm	

CO	Range	1-1000	10^{-2} (%) Vol.
	Resolution	0.01%	
CO_2	Range	0-20	10^{-2} (%) Vol.
	Resolution	0.01% Vol.	

2.2 Engine Setup

Figure 2 illustrates the experimental arrangement for an engine that has a Maximum power of 3.5 kW. with direct injection. The engine was coupled to an eddy current dynamometer to control and measure the load conditions.

Various sensors and equipment were installed to record parameters like fuel consumption rate, exhaust temperature, and engine speed. Technical Specifications of Test Rig Equipment are found in Table 1.

Each test cycle at selected torque consists of running the engine for 1 minute at idle speed and 9 minutes at selected load under test cycle G3 of ISO 8178 – 4 [4]. The engine-rated power was taken as 100% load. The Test cycles were repeated for 20%, 40%, 60% and 80% load. This test cycle procedure was followed for diesel, Jatropha, Moringa and waste oil biodiesel.

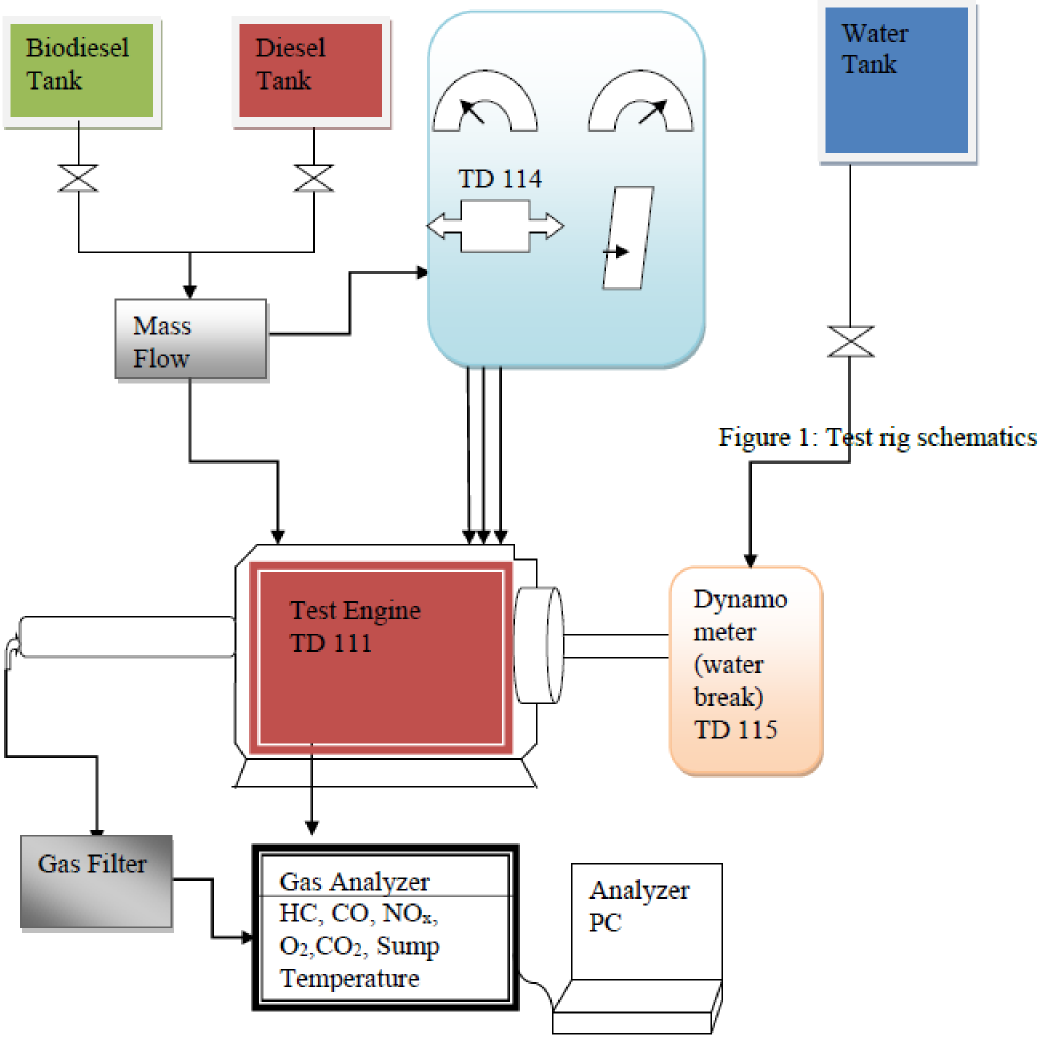


Figure 2. Experimental setup

The SV-5Q exhaust gas analyzer was, following the ND112 (Non-Dispersive infra-Red) method utilized via microcomputer analysis to measure the thickness of HC, CO and CO_2 in the exhaust gas and to inspect the density of NO_X and O_2 via Electrochemical sensor. The excess air coefficient, λ was also computed automatically by the analyzer and double-checked manually to confirm accuracy. The analyzer is equipped with a microprocessor, an induction tachometer, a temperature sensor, and an inner microprinter. The exhaust gas sampling probe inserted in the exhaust line draws exhaust gas through a filter enroute to the gas analyzer, the filter packing, made of cotton, traps PM with particle size greater than 10 microns. The filter packing is replaced at the end of every test cycle and the weight difference between used and unused packing is noted to compute the average PM emission per test cycle. A weighting device with 1microgram resolution was used to weigh the filter pack. Given the standard measure stipulated by ISO8178-4, it was necessary to convert this measurement into g/kWh using the air and fuel flow method [13].

The test was conducted in Bauchi, a North-Eastern Nigerian town located on latitude 10^o 18’ 57” N and longitude 09^o 50’ 39” E at an elevation of 2,021ft (616m). The prevailing ambient temperature at the time of the test ranges between 30 – 33^o C and the relative humidity between 71 -75%. The recorded atmospheric pressure was 92kPa, air density was 1.208kg/m^3 and absolute humidity, was 0.022kg/m^3 from these data, the specific humidity was computed.

3.0 Result and Discussion

3.1 Extraction Yield, Oil and Biodiesel Properties

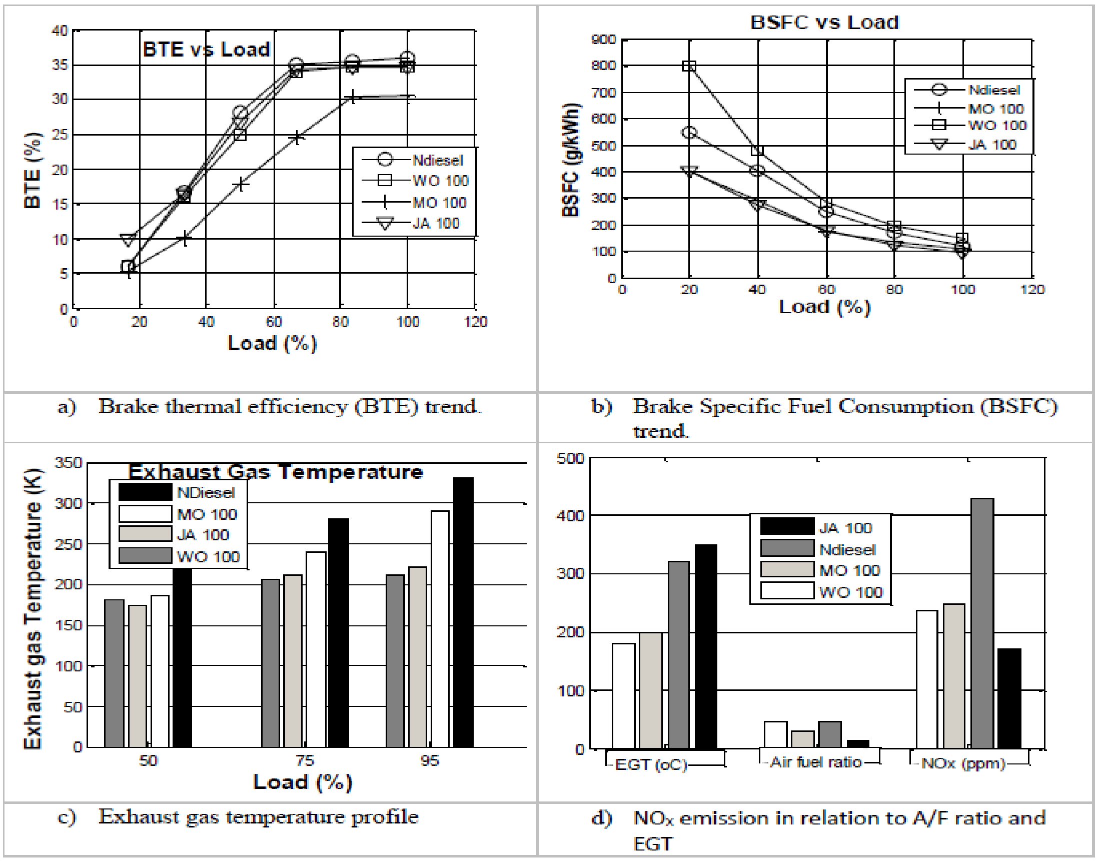
Results obtained from the extraction yield (shown in Table 1a) indicated that Soxhlet extraction was found to be the optimal method of extraction as it showed a nearly 50% yield above manual soaking method for all types of solvent with both samples. N–hexane was found to be a more efficient solvent in the extraction process followed by distilled gasoline while petroleum ether gave a sub-optimal yield of 24.3% for Moringa and 25.3% for Jatropha using the Soxhlet method. All the solvents, post-extraction, were recoverable. It is worthnoting that distilled gasoline, that was introduced as a wildcard gave satisfactory results. This is an important outcome given the ready availability of gasoline. The extraction yield result is broadly in agreement with previous work done under similar conditions [14-16]. The superior yield observed for Soxhlet in comparison to the soaking method underscores the importance of intense interaction between seed oil matrix with solvent. The differential yield for the various solvents shows the level of impact solubility has on seed oil extraction.

For the physio-chemical properties, Table 1(b)shows results obtained from various experimentsconducted on the oil extracts. These results are within the range obtained for oil processed into biodiesel for diesel engine application. Table 1(c) also shows the fuel properties of the biodiesel produced from Moringa (MO100), Jatropha (JA100) and Waste Restaurant Oil (WO100). Thedata shows good agreement with the ASTM standard for diesel engine fuel.

3.2 Engine Performance

At the engine speed of 1800rpm, Moringa biodiesel (MO100) experiences a brake torque loss of 6.97% in comparison to diesel at the torque of 8.6Nm.This loss increased to 7.69% as the torque reduced to 6.5Nm. The trend is repeated in varying degrees as the engine is running with WO100 and JA100. The brake torque losses were generally within the range of 6-9%. These losses are attributed to the lower heating values and higher viscosity for the pure biodiesel, where the heating value decreased, in comparison to diesel ranging between 5 and 7%.

Figure 2(a) shows a plot of brake thermal efficiency (BTE) and load. The BTE increases as the load increases for all the fuel types and the result showed no significant difference between diesel and biodiesel for loading <40%, as the load exceeds that value, diesel records an increasing range of between 2.5 to 8.9% over all the biodiesels. The highest range was recorded between it and MO100, besides diesel's higher heating value, the reason for this could also be found in the biodiesel’s fatty acid methyl ester (FAME) composition. Among the samples tested, MO100 has the most unsaturated FAME in its composition and, these are known to have lower reactivity and cetane number [17]. This advantage is narrowed for lower-rated engines particularly given the higher brake specific fuel consumption (BSFC) and fuel conversion efficiency (As a result of biodiesel oxygenated molecule) for the biodiesel with its higher level of unsaturation, fuel conversion efficiency is slightly impeded. This result largely agrees with the earlier report [18].



a) Brake thermal efficiency (BTE) trend.

b) Brake Specific Fuel Consumption (BSFC) trend.

c) Exhaust gas temperature profile

d) NO_x emission in relation to A/F ratio and EGT

Figure 2: Engine performance

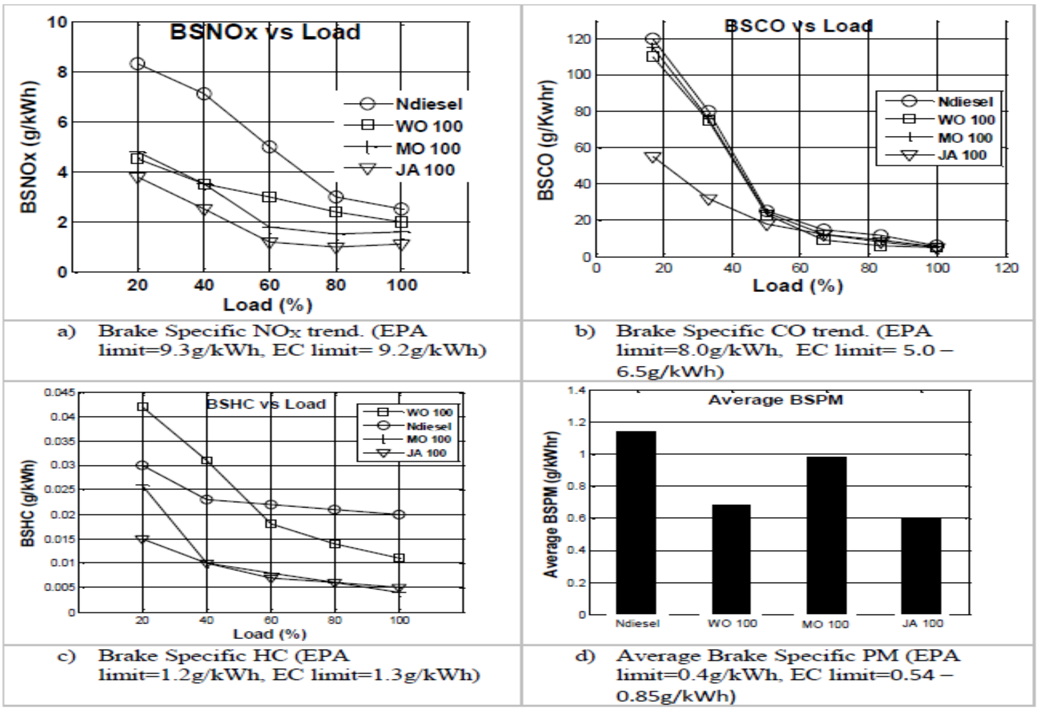
Figure 2(b) gives the relationship between the BSFCand load. The trend shows a general decrease in BSFC at increasing load profile with most of the decrease taking place between 20% to 60% load (a decrease of between 400g/kWh to 200g/kWh). M0100 showed a higher BSFC trend in comparisonto diesel. The difference, however, decreases from about 250g/kWh to 20g/kWh at peak load. Surprisingly, W0100 and JA100 (which recorded no significant difference between their BSFC) showed a trend lower than diesel starting from a difference of about 100g/kWh at 20% to less than 15% at peak load. Most work showed the opposite trend [9, 11]. The comparative advantage observed here for W0100 and JA100 for diesel is the result of the engine scale. At 3.5kW rated power, initiating and sustaining combustion is a bit challenging, this gives some edge to oxygenatedfuel with higher cetane number.

A slightly higher viscosity and lower heating value combine to impede fuel flow, heat release and in effect power delivery when the engine is run on pure biodiesel. These constraints become more obvious when the exhaust gas temperature of the various fuel types at 50%, 75% and 95% load are compared. Normal diesel, given its higher heating value and lower viscosity, is seen delivering higher power through a higher heat release rate. Spotlogging of exhaust gas temperature, as shown in Figure 1(c) is an easy gauge for this. At 95% load MO100 which had the best exhaust gas temperature (EGT) logged amongst the biodiesel had its maximum temperature less than that of NDiesel by about 9%. The average exhaust gas temperature decreases of the three biodiesel at all the loading ranges between 11 – 14%. This is well above the heating value decrease of between 5 – 7%. This could mean that the advantage of lower viscosity for NDiesel is more significant than the advantage of more efficient combustion for biodieselwhen the heat release rate is considered.

3.3 Pollutant Emission

The pollutant NO_X, THC, CO and PM were measured per ISO 8178 with a constant speed test cycle prescribed in test cycle D1. Most engines of this category operate at a constant speed with a loading profile in the range of 50% and above. The gas analyser, SV-5Q was used to measure NO_X, THC and CO in ppm and the result was converted to g/kWh. The trend observed for the emissions is presented in Figure 3 and discoursed below.

As expected, the NO_x in ppm increases with increasing load. The results show a mixed trend with MO100 and JA100 having higher values at low loading conditions when compared with normal diesel, but as the load increases, normal diesel's NO_xmeasure increases well above the biodiesel fuel type. Historically, NO_x emission has been observed to be higher for biodiesel than for Normal diesel [8, 19- 22]. This result, taken its face value may appear to paint an opposite picture but that is not the case because NO_x production in the internal combustion engine is driven by the extended Zeldovich mechanism which describes the oxidation of atmospheric nitrogen into NO_x by a three-step reaction which has a strong temperature (because of large activation energy) and 0_2 concentration dependence. A comparative study of NQ_x emission for different fuel types can only be done quantitatively at similar temperatures and excess air regimes. Biodiesel typically has been observed to produce more NO_x because given their oxygenated molecule, a higher O_2 concentration was prevalent in the reaction zone but this only happens in a constrained oxygen environment. Brakora and Reitz [23] using SENKIN code in a computational study observed that in excess air environment, diesel produces more NO_X. Coincidentally in this test, when a comparative evaluation of NO_x emission for all the test cycles was done againstexcess air and temperature, it was observed that maximum NO_x emission was observed at the pointof highest temperature and excess air regardless of the fuel type. This is shown in Figure 2(d). The $BSNO_x$ vs load trend shown in Figure 3(a) points to a decreasing emission with increasing load for all the fuel types. All the biodiesel fuel showed $BSNO_x$ levels lower than normal diesel even when the decrease is more rapid for normal diesel. The $BSNO_x$ decrease rate appears to plateau between 65% load to maximum load which corresponds to a point of stable temperature and excess air. The data did not breach EPA and EC emission caps.



a) Brake Specific NOx trend. (EPA limit=9.3g/kWh, EC limit= 9.2g/kWh)

b) Brake Specific CO trend. (EPA limit=8.0g/kWh, EC limit= 5.0 – 6.5g/kWh)

c) Brake Specific HC (EPA limit=1.2g/kWh, EC limit=1.3g/kWh)

d) Average Brake Specific PM (EPA limit=0.4g/kWh, EC limit=0.54 – 0.85g/kWh)

Figure 3: Engine specific emission

CO in ppm emission decreased with increasing load and normal diesel CO emission was highest at all loading conditions A similar trend has been observed and reported extensively [24-27]. The oxygenated nature of biodiesel accounts for this trend. The CO emission, when measured in ppm for all fuel types appears insignificant at increasing load but in BSCO stipulated by the EPA and EC as shown in figure 3(b), the emission caps were breached by all fuel types. Normal diesel still gave the most emission albeit at a much-reduced margin except for JA100 within the loading profile of between 20 – 50%. Given the emission cap standard of 8g/kWh and 5 -6g/kWh by the EPA and the EU respectively for CO emission, at between 20 -65% loading for all the fuel types, the emission standard for CO was in breach. It could also be seen that Normal diesel failed to meet the standard until it reached 80% loading.

CO emission measure in ppm was observed to increase with increasing temperature for normal diesel by as much as 0.0064ppm/^{0}C. This trend suggests that CO production, although primarily equilibrium-based, is kinetically driven. At higher combustion temperatures, gas dissociation of CO_2 into CO takes place and during the rapid expansion (common with fast stroke action) stage, burnt gas assumes a frozen state thus preventing the oxidationof CO back to CO_2 in the exhaust [28].

HC (measured in ppm) emission was observed to reduce when pure biodiesel replaced Normal diesel. The reduction on average is 16.5% for WO100, 50% for MO100 and 67.5% for JA100. For all fuel types, between 20% to 40% load, HC emission reduces at between 2-5%. Primarily four mechanisms exist through which HC is produced in the engine [31]. The first is flame quenching in the combustion chamber wall, the second, is an unburned mixture of crevice volume, the third, is absorption and de-absorption of fuel into/out of oil layers during intake and compression and finally, incomplete combustion of fuel during combustion. Of these four mechanisms, normal diesel and biodiesel have similar behavior in the first three. Only in the last mechanism does normal diesel differ from pure biodiesel because of fuel chemistry. That is, given the oxygenated nature and high cetane number of pure biodiesels, combustion is more likely to be initiated earlier and proceeds in a more complete fashion than it will be for normal diesel [29-31]. Figure 3(c) gives the BSHC versus load. The trend shows that BSHC decreases rapidly with increasing load from 20% to 50% load, thereafter the reduction becomes more gradual. The important thing to note is that the highest recorded BSHC for all the fuel types was less than the proposed regulated limit for the European Commission (1.3g/kWh) and the US EPA (1.2g/kWh). It is clear here that improved combustion efficiency places biodiesel at an advantage in terms of BSHC emission.

Particulate Matter is primarily measured via two approaches, namely, mass-based PM measure and Bosch smoke number [32]. The mass-based measure, adopted in this work, is the measure regulated by the US Environmental Protection Agency and the EC [9]. Figure 3(d) gives the weighted average PM emission for Normal diesel, W0100, M0100 and JA100. Normal diesel peaked at 1.14g/kWh. W0 100, M0100 and JA100 showed40.3%, 14.0% and 47.3% reduction in PM emissionrespectively when compared with normal diesel PM emission. The US EPA and EC standard regulations prescribed that PM should be less than 0.4g/kWh and 0.54 -0.85g/kWh respectively this showed that normal diesel and M0100 PM Emissions in this work failed to meet both standards. It also showed that W0100 and JA100 passed the upper limit of the EU standard but failed the US EPA standard. The absence of aromatics and Sulphur in pure biodiesel is the primary reason for the reduction inPM for biodiesel fuels [33].

4.0 Conclusion

Given its renewable nature, sustainability, and varied sources, biodiesel fuel is set to play an important role in the energy mix of the future. The conclusion drawn from this work is that, at the production and extraction level, this fuel source potential is dynamic and evolving. The performance gap between it and normal diesel can be engineered to a tolerable level as novel engines are developed. Some of the unfavorable emissions have root causes in the fuel chemistry but are largely driven by engine conditions which can be mitigated with low-temperature combustion (LTC) and a tighter control of excess air with Exhaust Gas Recirculation (EGR) engine technology. Given biodiesel-oxygenated fuel molecules and higher cetane value, an EGR and LTC regime will not be much of a challenge. Emissions may be measured in Brake Specific terms, compared with emission caps and normal diesel broadly defines the extent of remediation needed to align the fuel source to an acceptable level.

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