Performance Evaluation of Biodiesel-Biodiesel Blends in a Dedicated CIDI Engine

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Abstract-Characteristics of biodiesel from Palm Kernel Oil Methyl Ester (PKOME), Jatropha Curcas Methyl Ester (JCME) & Coconut Oil Methyl Ester (COME) and their blends have been determined to run in a compression ignition direct injection (CIDI) internal combustion engine. The vegetable oils of Ghanaian origin (PKOME, COME and JCME) were converted to biodiesel by transesterification. Optimum amount of catalysts including 1% H_2SO_4, 1% NaOH and methanol: oil ratio between 6:1 and 8:1 produced the best yields of the biodiesels. The biodiesels were run in a VW diesel engine in an experiment. PKOME and COME were blended in proportions of 100%, 75%, 50% and 25% to determine the best blend for optimum physiochemical properties and engine performance. JCME was also blended with COME in the same proportions. Exhaust emissions and fuel consumption best values were obtained with 75% COME and 25% PKOME at desirability of 97% with brake specific energy consumption (BSEC) of 15.4 MJ/kWh, CO (0.39 Vol. %), HC (45 ppm) and NOx (146 ppm). The best blend JCME and COME was in the proportion 75% JCME and 25% COME with BSEC of 13 MJ/kW h and CO, HC and NOx emissions of 0.24 Vol. %, 65 ppm and 256 ppm respectively. The best blends made engine performance properties close to petroleum diesel (BSEC= 11.8 MJ/kW h, CO=0.43 Vol. %, HC=103 ppm, NOx= 140 ppm). Therefore blends of JCME (75%) and COME (25%) produced better engine performance than petroleum diesel CO by 80% and HC by 58%. The result show that blending biodiesel of different feedstock can improve CIDI engine performance and exhaust emissions.

Keywords— *Biodiesel; Jatropha; Palm Kernel Oil; Coconut Oil, Renewable Energy*

1. Introduction

Diesel fuels have an essential function in the industrial economy of a country with applications in heavy trucks, city transport buses, locomotives, generators, farm equipment, earthmoving and underground mining equipment. From the point of view of protecting the global environment and the concern for long term supplies of conventional diesel fuels, it becomes necessary to develop alternative fuels which are comparable to conventional fuels. The substitution of even a small fraction of total consumption by alternative fuels will have a significant impact on the economy and the environment. Jatropha oil, coconut oil and Palm kernel oil holds the key to rural development.

Increasing industrialization of the world has led to a rise for the demand of petroleum-based fuels [1]. Today fossil fuels take up 80% of the primary energy consumed in the world, of which 58% alone is consumed by the transport sector [2]. It has been estimated that oil production will show a downward trend to become just 35% of today's production by the year 2075 [3]. According to the International Energy Agency, from 2000 through 2008, global diesel (also called gasoil or distillate in some parts of the world) consumption increased by 23%, while consumption of other petroleum products grew by 7%.

Unfortunately the use of biodiesel is hindered by two major social factors. First, it is edible and hence its use as biodiesel competes with its use as food. Secondly, the feedstock might not be readily abundant. For instance, the most readily available feedstock for production of biodiesel in Ghana is Palm oil. However Ghana is a net importer of palm oil [4]. But it will be more realistic if it is blended with biodiesels from other feedstock such as palm kernel oil, coconut oil or Jatropha oil which are also readily available but not preferred compared to palm oil.

When Rudolph Diesel invented the Compression ignition engine he used Peanut Oil, a type of raw vegetable oil as fuel [5]. The engine, which had been developed to run on diesel oils, worked with vegetable oil without any modification. Physical properties of Vegetable oils are close to those of diesel oil and therefore are similar fuels. However several issues have been reported with the use of vegetable oils in diesel engines. Because of the low Cetane number and high viscosity of vegetable oil several difficulties in diesel engines such as engine chocking, Injector coking, gum formation, clogged filters, and deposits in the combustion chamber under long term use have been reported [6].

Table 1. Work done on the three feedstocks

Feedstock	Proportion	Engine	Methodology	References
PKOME	B100 (no blending)	no engine tests conducted	Biodiesel production	[7,8,9,10,11,12,13,14,15]
COME	B20(blends with petrodiesel)	4-cylinder diesel engine	Emissions test, BSFC	[16,17,18,19]
	B100(no blending)	No engine tests	Properties	[20,21,22,23,24]
JCME	B20 and B50 blends with petrodiesel	Engine tests	Engine performance	[25,26,27,28,29]
	B100 (no blends)	No engine tests	Emissions	[30,31]
	B100 (no blending)	Engine tests		[26]

What is unknown in literature is whether blending biodiesels of different feed stocks could improve the physiochemical properties and engine performance of the biodiesel. If it is favourable to replace petro-diesel, then how favourable is it and what percentages of blends are appropriate for specific feedstocks? Much research has been done on biodiesel blends with petroleum diesel but little is known if any of biodiesel/biodiesel blends (Table 1).

Investigations on engine performance and emissions for combined palm kernel oil and coconut oil or combined coconut oil and Jatropha oil were not found in scientific indexes. This research focusses on using combined palm kernel oil and coconut oil as well as coconut oil and Jatropha oil to improve their properties and engine performance. Performance and Emission results for the combine blends in a four cylinder diesel engine are shown graphically and compared with petroleum diesel, PKOME-COME and JCME-COME blends.

As Table 1 depicts no engine research has been carried out for PKOME let alone it blends with biodiesel of other feedstocks. Though engine runs have been conducted for coconut oil biodiesel or COME, only its blends with petrodiesel up till B20 have been considered. No further research of its B100 with other biodiesel feedstocks is reported in literature. This is the same for JCME where engine runs have been up till B50. Only Bhupendra et al. [31] conducted engine runs on B100, however they failed to conduct engine runs for JCME blends with other biodiesel feedstocks.

The focus of this research henceforth is on analysis of blends of palm kernel oil biodiesel, coconut oil and Jatropha biodiesel to determine optimum physio-chemical properties, engine emissions and fuel consumption. Best blend of each feedstock for optimized engine performance is suggested as well as their comparison with petrodiesel is analysed.

2. Materials and Methods

2.1. Fuel Preparation

Fuel preparation deals with how raw vegetable oils of palm kernel, coconut and Jatropha were converted to biodiesel. The process of conversion used is termed transesterification. Base-catalysed (Trans) esterification is used in this work since Acid-catalysed (Trans) esterification requires a much longer time. A base-catalysed esterification using NaOH to convert FFAs in the vegetable oil to methyl esters to reduce FFA was carried out for an hour. In the second step acid-catalysed Trans esterification was carried out where the pre-treated oil were then converted to methyl ester to further reduce FFA and hence the viscosity.

Both esterification and (Trans) esterification were conducted in a laboratory-scale experiment. The raw vegetable oil (200g) was pre-heated for an hour to ensure removal of water as a precaution of the oil probably not being well prepared. The pre-heating was terminated when visual inspection showed there were no more bubbles. For all test runs for the variations, temperature was kept constant and stirring was at same speed. Methanol mixed with NaOH was added to the pre-heated coconut mixture in the flat bottom reaction flask and stirred for an hour. The mixture was stirred for some time at the same rate and time for all test runs. In the second step H_2SO_4 was added to the pre-treated mixture and quickly stirred for about an hour. The essence of adding H_2SO_4 was to further reduce FFA and hence the viscosity of the biodiesel. Wet washing was then carried out with hot distilled water at 60°C and then dried to obtain the Coconut oil biodiesel. The same procedure was carried for Palm kernel oil and Jatropha oil.

2.2. Experimental Matrix

Physiochemical properties of JCME, PKOME, COME and their biodiesel/biodiesel blends were measured at the laboratory. ASTMD 6751 and EN 14214 standard fuel tests were conducted on JCME, PKOME and COME produced. Viscosity and Density measurements were made using Calibrated Capillary Glass Viscometer and Hydrometer, following ASTM D445 and ASTM D1298 respectively. Biodiesels of coconut and palm kernel oil were blended in various proportions as shown in Table 2.

Table 2. Experimental matrix for COME and PKOME blends

Run	**Component1 A: COME (%)**	**Component 2 B: PKOME (%)**	**Response1 BSEC (MJ/kW h)**	**Response2 CO (Vol. %)**	**Response3 HC(ppm)**	**Response 4 (ppm)**
1	0.00	100.00				
2	25.00	75.00				
3	75.00	25.00				
4	0.00	100.00				
5	50.00	50.00				
6	100.00	0.00				

Biodiesels of Jatropha and coconut oil were blended in proportions depicted by the experimental matrix in Table 3.

Table 3. Experimental matrix for JCME and COME blends

Run	**Component1 A:** JCME **(%)**	**Component 2** B: COME **(%)**	**Response1 BSEC (MJ/kW h)**	**Response2 CO (Vol. %)**	**Response3 HC(ppm)**	**Response 4 (ppm)**
1	0.00	100.00				
2	25.00	75.00				
3	75.00	25.00				
4	0.00	100.00				
5	50.00	50.00				
6	100.00	0.00				

Cetane Number of the three samples were measured using the Bracketing Hand Wheel procedure following ASTM D976. For all the samples Bomb Calorimeter was used to measure the Heating Values according to ASTM D 240. An experimental matrix was designed with Design-Expert 7.0 (Table 2 and 3) to conduct engine emission and performance tests.

2.3. Experimental Set-up

- A 4-cylinder VW diesel engine set-up was used as specified in Table 4.

Table 4. Specifications of engine used

Engine specification	**Details**
Engine make	VW Golf 3 water-cooled
Bore x Stroke	79.5x95.5mm
Aspiration	Turbo
Rated power	55kW
Rated speed	4200rpm
Compression ratio	22.5
Injection timing	336^0 CAD
Injection pressure	150 bar
Fuel type/system	Diesel/Bosch
Engine size/cylinders	$1.896cm^3$/4cylindes
Engine dynamometer	Alternator with water heaters

Exhaust gas composition was measured using AVL 5 gas exhaust gas analyser (Make: AVL Austria; Model: TG DiGas 5400). This analyser measures CO2, CO, HC, NOx and O2 in the exhaust gas. The measurement range and accuracy of the exhaust gas analyser are given in Table 5.

Table 5. Measurement range of exhaust analyser used

Exhaust gas analyser		
Exhaust gas	**Measurement range**	**Accuracy**
CO	0-10 % vol.	<.06 vol.%:±0.03 vol.% P0.6 vol.%:±5% of ind. val.
HC	0-20,000 ppm vol.	<200 ppm vol.:±10 ppm vol.
NO	0-5000 ppm vol.	P500 ppm vol.:±10% of ind. val.

Palm kernel oil methyl ester (PKOME) was characterised together with coconut oil methyl ester (COME), Jatropha Curcas Methyl Ester (JCME) and petroleum diesel according to the ASTM D6751.Table 6 shows the properties obtained in comparison with petroleum diesel and international standards.

Table 6. physiochemical properties obtained for JCME, PKOME and COME

Properties	JCME	PKOME	COME	Petro Diesel	ASTM D6751	EN 14214
Kinematic Viscosity @ 40°C (mm²/s)	3.1	3.7	2.4	2.6	1.9-6	3.5-5
Cetane number	52	50	55	49	47 min	51min
Pour point (°C)	-9	1	-5	1	-15 to 6	-
Cloud point (°C)	-6	6	2	2	-	-
Flash point (°C)	175	170	122	90	93 min	120 min
High calorific value (MJ/kg)	42	44	42	46	-	35
Acid value (mol %)	2	3.4	2	0.17	0.5 max	0.5 max
Density (kg/m³)	870	878	894	839	880	860-900

3. Results and Discussions

Palm kernel oil biodiesel and coconut oil biodiesel were blended in proportions of 100%, 75%, 50%, 25% and 0% to determine optimum physiochemical properties and engine performance. Fuel properties of cetane number, calorific value, density and viscosity was measured for each of the blends.

3.1. *Effects of PKOME-COME Blends on Properties*

The results obtained from the blends of PKOME and COME at different percentages is presented in Table 7.

Table 7. Physiochemical properties of PKOME-COME blends

Run	Component 1 A: COME (%)	Component 2 B: PKOME (%)	Response1 Calorific Value (MJ/kW h)	Response2 Viscosity (Cst)	Response3 Density (Kg/m³)	Response 4 Cetane Number
1	0.00	100.00	46	3.7	878	50
2	25.00	75.00	44.5	3.3	881	51
3	75.00	25.00	42.8	2.8	890	54
5	50.00	50.00	43.2	3	886	52
6	100.00	0.00	42	2.6	894	55

Design Expert software version 9, was used for the mixture analysis because of its simplicity, efficiency and popularity of use among researchers in this field.

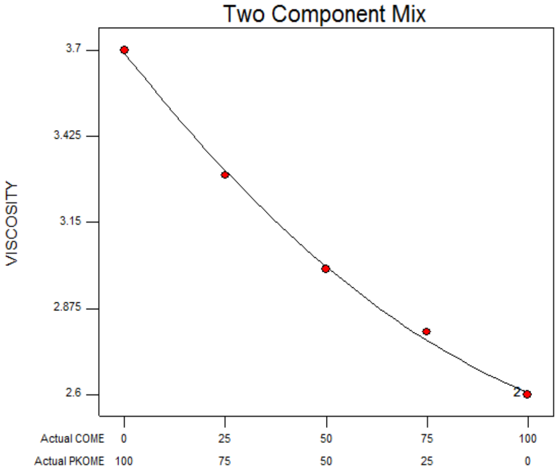

Figure 1. Viscosity of PKOME-COME blends

The lower the viscosity the better. Viscosity of the PKOME-COME component mix improved as COME percentage increased in the mixture (Figure 1). This is primarily because the sample of COME used originally had a low viscosity. Best blend for optimum viscosity was 25% PKOME and 75% COME at approximately 2.8Cst comparable to petroleum diesel viscosity of 3.2Cst

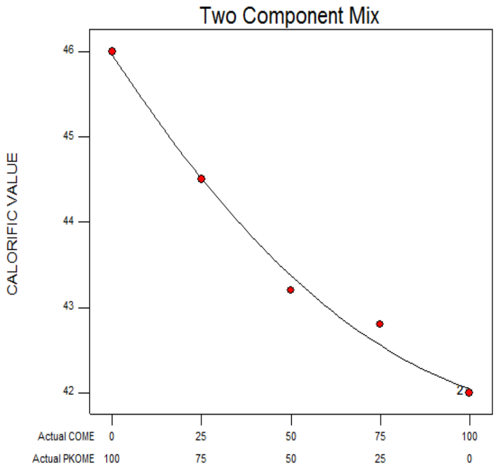

Figure 2. Calorific value of PKOME-COME blends

Calorific values can be used to distinguish among different fuels their likelihood to produce more or less power or torque per the same volume. It compares the energy content per litre for the various fuels under consideration. Figure 2, shows the Calorific values obtained for COME, PKOME and their blends compared with petroleum diesel. Coconut oil biodiesel has the lowest heating value at 42Mj/kg but a blend with 75% PKOME increased the value to 44.3Mj/kg. Biodiesel has generally been reported to have lesser Heating value [32].This is because for biodiesel, carbon and hydrogen are the sources of thermal energy while oxygen is ballast. Petroleum diesel fuel is made up of a mixture of various hydrocarbon molecules and contain little oxygen (less than 0.3%), while biodiesel contain significant amount of oxygen (10%). Hence due to its high oxygen content, biodiesel has lower Heating values than petroleum diesel [33].

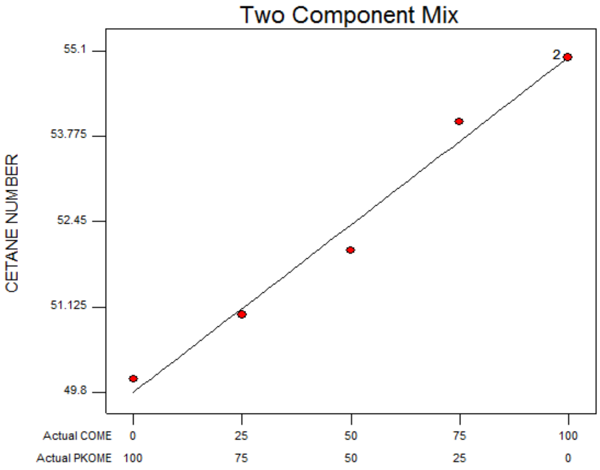

Figure 3. Cetane number of PKOME-COME blends

Cetane number (CN) is an indicator of the quality of fuel used in Compression Ignition (CI) engines. It is dimensionless and related to ignition delay (ID) time, the time that passes between injection of the fuel and start of ignition. A shorter ID corresponds to a higher CN and vice versa [34]. It is noticed from figure 3, that the biodiesel with the closest CN to petroleum diesel (CN=49) is PKOME (CN=48). It is also seen that COME had the more favourable CN of 55 and the best blend for improved CN is 25% PKOME and 75% COME at CN of 54.

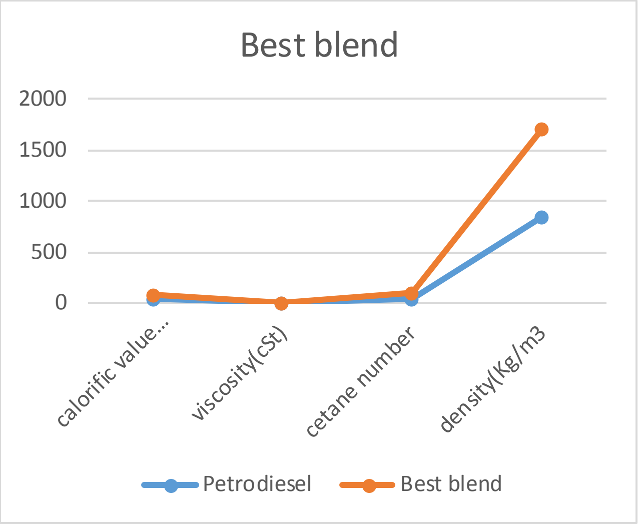

Figure 4. Comparison of best PKOME-COME blend properties with petroleum diesel (coloured)

All the blends have produced physiochemical properties similar to petro-diesel. However, the four most important properties for diesel fuel include viscosity, heating value, cetane number and density. Design expert, a design of experiment tool, was used to predict the best blend for COME and PKOME. Blend of COME (35%) with PKOME (65%) gave the best fuel properties with a desirability of 62.6%. As depicted by Figure 4, fuel properties of the optimum blend are very close to petroleum diesel. The greatest disparity lie with the densities with the best blend having a higher density or mass per unit volume. High densities are not an issue with diesel engines.

3.2. Effects of PKOME-COME Blends on Emissions

Emissions and fuel consumption analysis were conducted through engine runs for specified blends of PKOME and COME. The results are depicted in Table 8.

Table 8. engine performance results for PKOME-COME blends

Run	**Component 1: COME (%)**	**Component 2: PKOME (%)**	**Response1 BSEC (MJ/kWh)**	**Response2 CO (Vol. %)**	**Response3 HC(ppm)**	**Response 4 NOx (ppm)**
1	0.00	100.00	14.6	0.69	69	244
2	25.00	75.00	14.8	0.53	59	205
3	**75.00**	**25.00**	**15.4**	**0.39**	**45**	**146**
4	50.00	50.00	15.1	0.45	40	180
5	100.0	0.00	15.5	0.32	39	140

Brake specific energy consumption is a measure of rate of fuel consumption and the higher the BSEC the lesser the energy content in the fuel. The higher the COME percentage the worst the fuel consumption of the mixture. This proves that PKOME which has the higher calorific value can be used to improve brake specific energy consumption of COME (Figure 5).

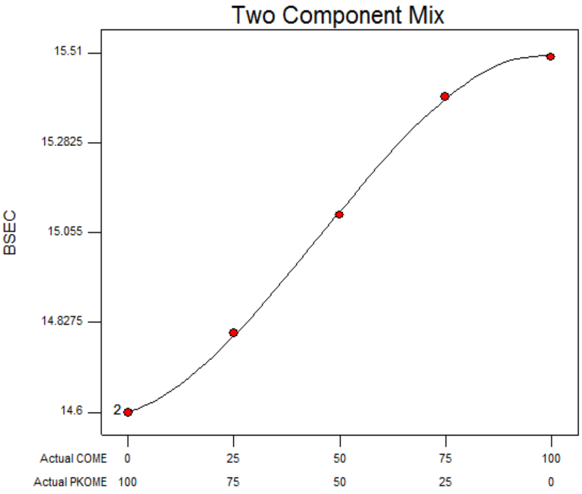

Figure 5. BSEC of PKOME-COME blends (coloured)

Maximum CO emissions (0.69 Vol.%) were obtained with 100% PKOME but as the COME component were increased to about 75% the COME emissions dwindled to 0.39Vol.% (Figure 6). similar results were obtained for HC emissions.

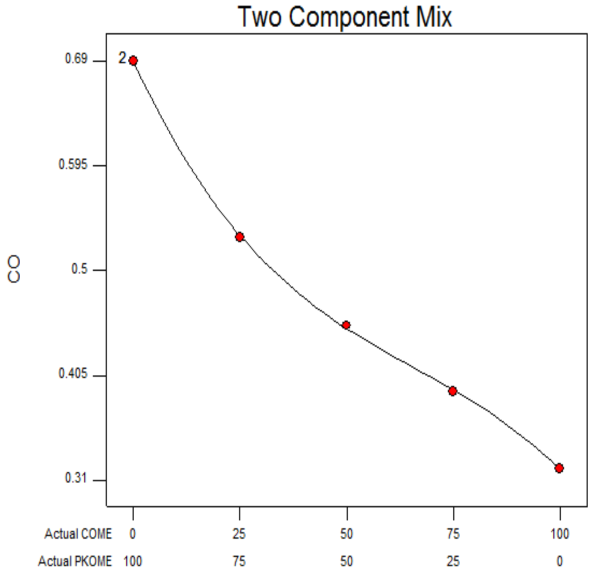

Figure 6. CO emissions of PKOME-COME blends (coloured)

NOx emissions as explained earlier are the nemesis of biodiesel emissions and the only emission element that surges with use of biodiesel. The results however prove that blending 25% PKOME with 75% of COME can lessen NOx emissions (Figure 7). Blending 25%PKOME with 75% COME lessened NOx emissions from 244ppm to 140ppm (43% reduction).

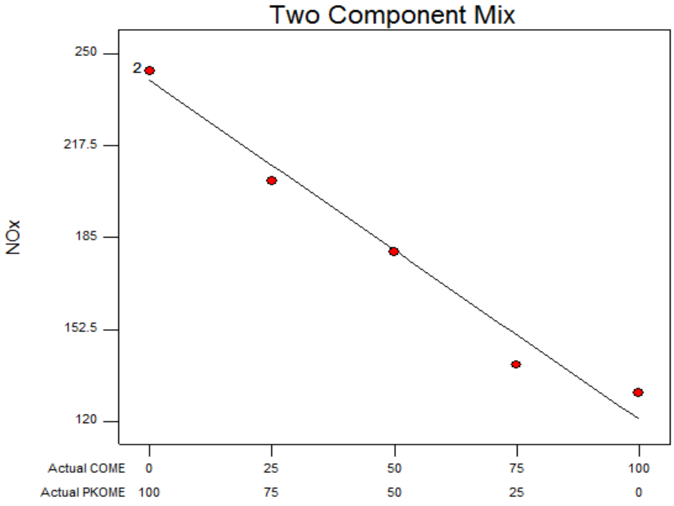

Figure 7 NOx emissions of PKOME-COME blends

3.2.1. Effects of JCME-COME Blends on emission

Emissions and fuel consumption analysis were conducted through engine runs for specified blends of JCME and COME. The results are depicted in Table 9.

Table 9. Engine performance results for JCME-COME blends

Brake specific energy consumption is a measure of rate of fuel consumption and the higher the BSEC the lesser the energy content in the fuel. BSEC is best when it is lowest.

Run	Component1 A: COME (%)	Component2 B: JCME (%)	Response1 BSEC (MJ/kW h)	Response2 CO (Vol.%)	Response3 HC(ppm)	Response 4 NOx (ppm)
1	0.00	100.00	12.6	0.22	60	310
2	**25.00**	**75.00**	**13**	**0.24**	**65**	**256**
3	75.00	25.00	13.7	0.3	82	180
4	50.00	50.00	14	0.28	75	207
5	100.00	0.00	15.5	0.32	92	130

The higher the COME percentage the worst the fuel consumption of the mixture (Figure 8). This proves that JCME which has the higher calorific value can be used to improve brake specific energy consumption of COME.

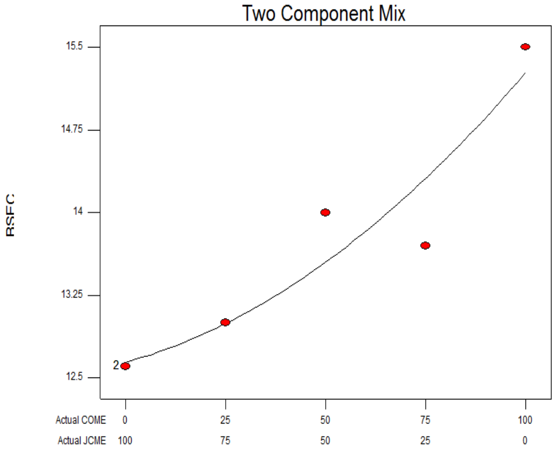

Figure 8. BSEC variation with JCME-COME blend

CO formation is as a result of incomplete combustion. This is when the flame front in the combustion chamber approaches a cool cylinder liner and is suddenly cooled down.

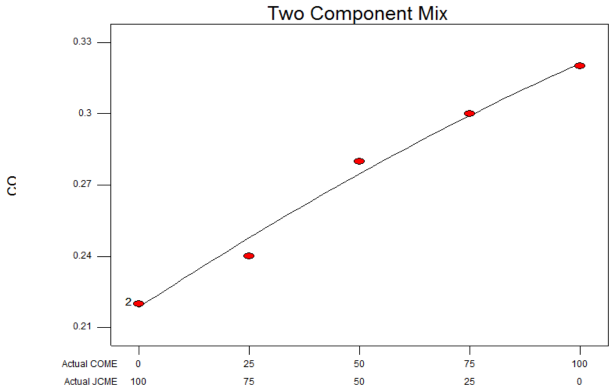

Figure 9. CO emission variation with JCME-COME blend

Maximum CO emissions (0.32 Vol.%) were obtained with 100% COME but as the JCME component were increased to about 75% the blend emissions reduced to 0.24Vol.% (Figure 9). similar results were obtained for HC emissions. It is well known that NOx emission is influenced by in-cylinder pressure, temperature and oxygen content of the fuel. Increasing JCME concentration in the blend reduces the NOx emissions (Figure 10).

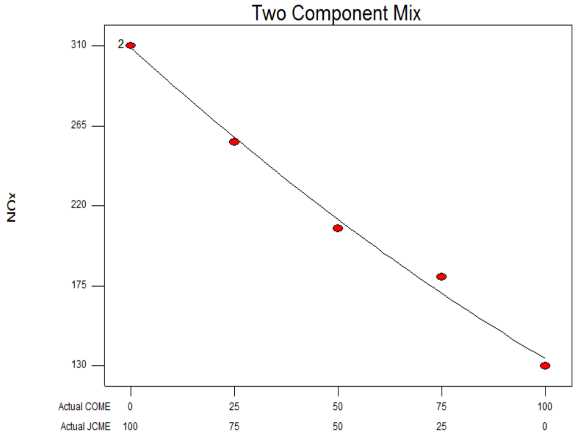

Figure 10. NOx emission variation with JCME-COME blends

Most desirable blend was obtained as 25% COME and 75% JCME with a desirability of 61%. With this blend 13MJ/kW h of brake specific energy was consumed and 0.24% of CO, 65ppm of HC and 256ppm of NOx emissions were recorded.

3.2.2. Blends Emissions Comparison with Petroleum Diesel

In terms of PKOME-COME the most desirable blend prediction and validation were obtained with 75% COME and 25% PKOME with a desirability of 97% but fuel consumption will surge as a result (15.4MJ/kW h). The reverse combination (75% PKOME and 25% COME) should be considered if the goal is to maximize fuel consumption at the expense of emissions.

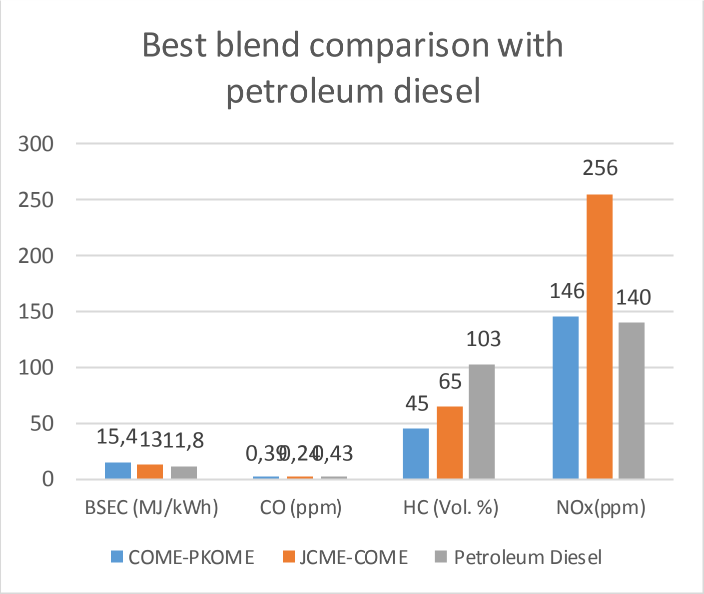

Figure 11. Comparison of best PKOME-COME blend engine performance with petroleum diesel (coloured)

In terms of JCME-COME the most desirable blend prediction and validation were obtained with 75% JCME and 25% COME with a desirability of 92%. Comparing best blends with petroleum diesel it is seen that Petroleum diesel has a lower fuel consumption compared to all the blends. It has already been explained that generally biodiesels have their fuel consumptions higher than petroleum diesel. The degree of difference being equivalent to the percentage of oxygen in biodiesel. In this case biodiesel contain approximately 10% more oxygen than petroleum diesel. Thus BSEC of JCME-COME (13MJ/kg) differs from petroleum (11.8MJ/kg) diesel by approximately 10%. This is not likely change no matter the blend since biodiesel has consistently lower heating value and lower stoichiometric air/fuel ratios than petroleum diesel. All the biodiesel blends recorded lower CO (PKOME-COME=0.39 ppm, JCME-COME=0.29 ppm) emissions compared with petroleum diesel (0.43 ppm). The trend was similar for HC emissions with PKOME-COME blend recording HC emissions of 128% lower than petroleum diesel. The disadvantage of biodiesel still lies with the NOx emissions since the higher concentration of oxygen in biodiesel makes its NOx emissions higher than petroleum diesel. However NOx emissions of COME-PKOME (146 ppm) obtained was very close to petroleum diesel (140 ppm).

This implies that blending biodiesel of different feedstocks could be the key to reducing NOx emissions of biodiesel fuelled engines.

4. Conclusion

PKOME & COME, JCME & COME were blended in proportions of 100%, 75%, 50%, 25% and 0% to determine optimum physiochemical properties and engine performance.

- In terms of emissions the most desirable blend prediction and validation were obtained with 75% COME and 25% PKOME with a desirability of 97% but fuel consumption will surge as a result (15.4MJ/kW h). The reverse combination (75% PKOME and 25% COME) should be considered if the goal is to minimize fuel consumption (14.8 MJ/kW h) at the expense of emissions.
- The optimized blends produced/made engine performance properties close to petroleum diesel (BSEC= 11.8 MJ/kW h, CO=0.43 Vol. %, HC=103 ppm, NOx= 140 ppm). Therefore blends of JCME (75%) and COME (25%) produced better engine performance than petroleum diesel CO by 80% and HC by 58%.
- The result prove that blending biodiesel of different feedstocks can improve their engine performance and emissions.

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