Engine performance and emissions of fuel produced from palm kernel oil

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ABSTRACT

In this research work, the experimental investigation on effect of preheating on the performance and emissions of a direct injection diesel engine has been reported. Four different fuels were tested using the same diesel engine: crude palm kernel oil (CPKO), preheated crude palm kernel oil (PCPKO), palm kernel oil methyl ester (PKOME) and petroleum diesel (petrodiesel) as reference fuel. A novel technique of using engine coolant to preheat the CPKO to PCPKO was employed. A bypass was created from the engine for the coolant to pass through and heat a series of coiled copper tubes inside the fuel tank and on which was the PCPKO. Preheating CPKO to obtain PCPKO reduced the viscosity by 59% and improved brake torque and brake power by 14%. BTE and BSFC of PCPKO was better than CPKO by 16% and 36%, respectively because the lowered viscosity of PCPKO facilitated a better atomization during combustion. While PKOME, biodiesel, recorded 21% less carbon monoxide and 71% less THC emissions than CPKO.

Keywords: Palm kernel oil ; crude vegetable oil ; biodiesel ; preheated vegetable oil ; engine performance

Nomenclature

CPKO	crude palm kernel oil
PCPKO	preheated crude palm kernel oil
PKOME	palm kernel oil methyl ester
BTE	brake thermal efficiency
PKO	palm kernel oil
CVO	crude vegetable oils
CO	carbon monoxide
THC	total hydrocarbons
CO_2	carbon dioxide
Petrodiesel	petroleum diesel
NOx	oxides of nitrogen
FFA	free fatty acids

Introduction

Biodiesel has been touted as the best replacement for petroleum diesel ahead of crude vegetable oils. It combines the advantage of its biodegradability with less emissions, moderate engine performance close to petroleum diesel and superior emissions especially with regards to carbon dioxide, carbon monoxide, hydrocarbon and smoke emissions [1]. But even the conversion of crude vegetable oil to biodiesel through the least expensive process of transesterification has its challenges. The cost of transesterification is still high, hindering the full commercialization of the fuel [2]. It adds to the cost of the fuel making it less competitive to petroleum diesel. Biodiesel is obtained from vegetable oils or animal fats though transesterification. The process of conversion to biodiesel adds to the cost of the fuel and requires the use of other fossil derived inputs such as methanol or ethanol [2].

Crude vegetable oils also called straight vegetable oils can be used in its natural form instead of converting to biodiesel for use in a compression ignition engine. When Crude vegetable oils (CVO) are used as alternative to petroleum diesel, the issue of price volatility and availability is avoided. CVO can be produced locally in most communities and villages in developing countries where petroleum fuels do not reach. Use of crude vegetable oil in compression ignition engines lead to lower CO, HC and soot formation. Biofuels have been proposed as alternatives to petroleum fuel due to pollution, rising cost of petroleum fuel prices and the issue of availability especially in the rural setting. The European Union plans to have 10% of the transport fuel of each of its member countries generated from renewable sources such as biofuels by 2020. This is because the transport sector has been identified as key contributor to global warming [3]. In the united states alone, over 90% of petroleum fuel consumption is attributed to the transport sector [4]. Though promising, many researchers have raised concerns about the durability and lifespan of engines fueled with crude vegetable oil [5]. Issues such as injector coking, lubrication oil dilution, pump seizure, cold starting and poor engine performance have been identified [6]. Some of the research focused on the effect of crude vegetable oil on wear of mechanical fuel injection system [7]. Operational issues have been reported as a result of such research and a number of recommendations have been made to reduce the viscosity of the vegetable oil and improve fuel atomization.

In this study, the engine performance and emissions from all the possible fuels that can be produced from palm kernel oil has been presented. Crude palm kernel oil (CPKO), preheated crude palm kernel oil (PCPKO), palm kernel oil methyl ester (PKOME) and a reference petrodiesel were all run in the same engine. A novel method of preheating the palm kernel oil using by channeling coolant from the engine through a series of copper papers in the fuel tank has been experimented also in this work. The crude palm kernel oil which is placed on the copper tubing gets heated by the coolant circulating through the copper tubing before reaching the radiator. A number of solutions have been suggested to reduce the viscosity of the crude vegetable oil. To solve the problem of poor fuel atomization other studies have also shown that adequately heating the vegetable oil before use reduces the viscosity, density, acid value, water contents and improves fuel atomization close to those of petroleum diesel [8]. Methods such as blending with petroleum diesel, varying of compression ratio, injector variation and preheating have all been employed to improve crude vegetable oil performance [9]. Chauhan et al, investigated the performance and emission of preheated Jatropha oil on medium capacity diesel engine [10]. They used exhaust gases as the mode of heating by designing a shell and tube heat exchanger with a bypass. Mustafa et al, studied combustion analysis of preheated crude sunflower oil used a heat exchanger to heat the sunflower oil [11]. Very often the means of heating the vegetable oil before use has either been by use of the hot exhaust gases or an electric heater [12, 13]. Other researches heated the crude vegetable oil externally [14]. The choice of feed stock, palm kernel oil, for this study is because rare information is found in literature on the possibility of using palm kernel oil as an alternative to petroleum diesel. The only information on engine performance of palm kernel oil have focused on palm kernel oil as a biodiesel, blends with petroleum diesel or as a waste vegetable oil to the neglect of CPKO or PCPKO [15–25~~15–26~~]. This study thus fills a huge gap in literature concerning the engine performance of the various forms of palm kernel oil as a renewable fuel alternative to petroleum diesel. The objective of this work is the compare the engine performance of palm kernel oil in its crude form, preheated form (using a novel method of preheating) and its biodiesel form to petroleum diesel.

Materials and methods

Design of experiment

Petrodiesel was obtained from Tema Oil Refinery in Ghana. Crude palm kernel oil (CPKO) were purchased from the open market in Ghana. Palm kernel oil methyl ester (PKOME) was produced through a transesterification process using ethanol with sodium hydroxide as catalyst. Each of the four fuels were characterized according to the ASTM standards.

Two different types of measurements were conducted for all the fuels as seen from Figure 1. Brake thermal efficiency (BTE), brake torque, brake power and brake specific fuel consumption (BSFC) were the engine performance parameters measured. Total hydrocarbon (THC), carbon monoxide (CO), Oxides of Nitrogen (NOx) and smoke were the emissions measured.

Figure 1. Design of experiment used to conduct engine performance and emissions run for petrodiesel, PCPKO, CPKO and PKOME.

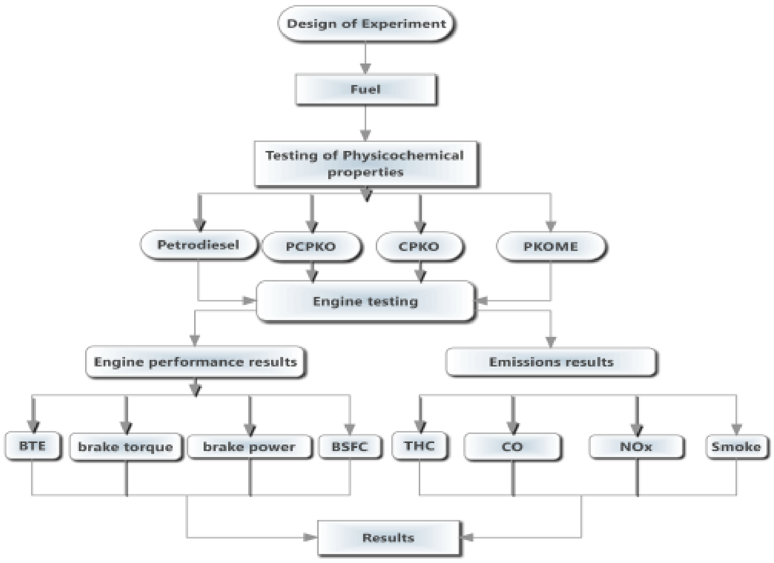
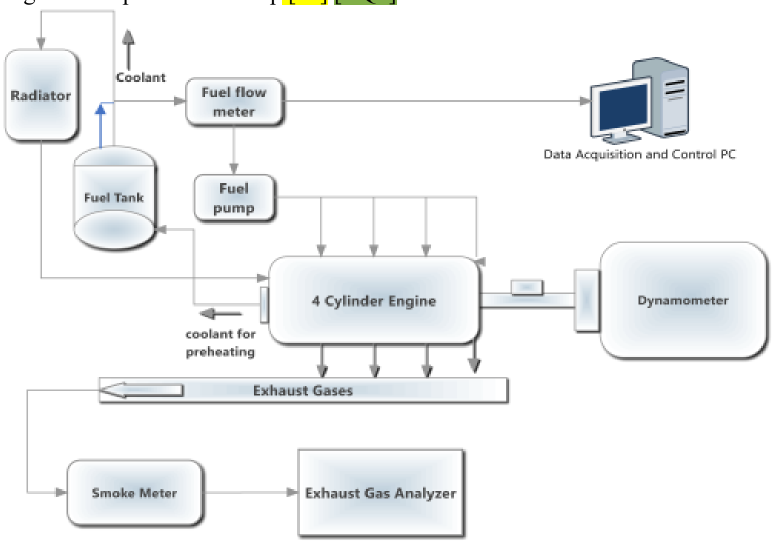


Figure 2. Experimental setup [10].[AQ9]



Physicochemical properties

Characterization of CPKO, PCPKO, PKOME and petrodiesel were conducted at the Ghana Standards Authority (GSA) laboratory under the following standards (Table 1).

Table 1. Physicochemical properties of fuels characterized and standards used.

Property	PCPKO	CPKO	PKOME	Petroleum diesel	Measurement standard used
Kinematic viscosity at 100 °C (Cst)	9	22	4.2	2.5	ASTM D445
Specific gravity	0.893	0.921	0.856		–
Cloud point (°C)	8	24	7.4	−12	ASTM 2500
Pour point (°C)	4	23	2	−17	ASTM 2500
Flashpoint (°C)	130	240	148	80	ASTM D93
Calorific value (MJ/kg)	38	38	43	47	ASTM D93
Cetane number	62	61	65	50	ASTM D613
Acid value (mgKOH/g)	0.92	3.2	–	–	ASTM D664
Iodine value (mgI_2/g)	18	18.2	15.1	–	

The biodiesel was produced using an alkaline-catalyzed esterification of NaOH to convert free fatty acids (FFA) in crude palm kernel oil to methyl esters. This process was carried out for an hour ~~is~~ to reduce FFA content. In the second step acid-catalyzed trans esterification was carried out. ~~t~~The pretreated oil was then converted to methyl ester to further reduce FFA content. Both esterification and (Trans) esterification were conducted in a laboratory-scale experiment. The raw vegetable oil (200 g) 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. In the second step H_2SO_4 mixed with the pretreated blend and quickly agitated for about an hour. The essence of adding H_2SO_4 was to further reduce FFA content 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 palm kernel oil biodiesel.

Experimental set up

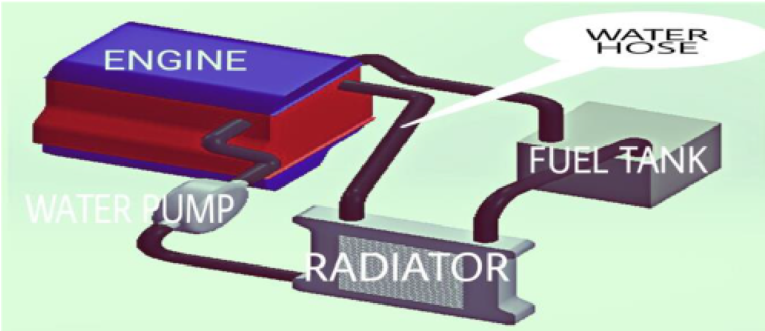
A four-cylinder Volkswagen engine was used for the experimentation of all four fuels (Table 2). The PCPKO was obtained as CPKO was preheated using coolant exiting the engine which is channeled via copper pipes inserted in the fuel tank. Preheating the kernel oil to 100 °C reduced the viscosity by 59% (Table 1).

Table 2. Engine specifications.

Item	Specifications
Bore × stroke (mm)	106.5 × 127.0
Connecting rod length (mm)	203.0
Compression ratio	17:1
Maximum power (kW)	66.5 at 3300 rpm
Number of cylinder	4
Engine type	Water cooled
Aspiration	Turbocharged
Fuel injection	Direct injection
Injection timing	336 °C
Injection pressure	150 bar
Engine dynamometer	Alternator with water heaters

The fuel tank was redesigned and installed according to the diagram in Figure 3. The coolant from the engine was channeled ~~to~~ through copper stripes carefully wound and placed in the bottom of the fuel tank. The copper stripes then ~~led~~ connected to the radiator. By this, the coolant heat was used to heat up the fuel tank to reduce the viscosity of the CPKO. The following procedure was followed.

Figure 3. preheating of palm kernel oil set-up.



- water hose from the engine coolant outlet was connected to the inlet of the copper pipe heat exchanger in the fuel tank with the regulator valve fixed in-between this connection.

Water hose from the fuel tank, specifically the outlet of the copper pipe heat exchanger was connected to the radiator coolant inlet.

- The coolant tank was filled to the right level.
- The engine was started.
- A record of the temperature of the engine and fuel tank was taken using an infrared thermometer right after the engine. The heating of the oil was done and controlled by a magnetic stirrer and hotplate. Further temperature readings were taken as the engine continued to run.

An AVL exhaust gas analyzer was used to measure emissions of THC, NOx and CO. A smoke meter was used to measure smoke emissions from the fuels.

Error/uncertainty analysis

Provision was made to limit the error margin as a result of the equipment involved, test conditions and the environment. Each experimentation ~~is~~was carried out five times and only the mean results are used. The mean's upper and lower limits are found from confidence intervals. The confidence limits were determined from the equation

$$X \pm t_{1-\frac{\alpha}{2}, N-1} \frac{\sigma}{\sqrt{N}}$$

X = mean, N = sample size, σ = standard deviation of the samples, $\alpha = 1 -$ (confidence level/100). $t_{1-\frac{\alpha}{2}, N-1}$ is $100(1-\frac{\alpha}{2})$ percentile value of the t-distribution at N – 1 degrees of freedom. In calculating the confidence level, the value of $t_{1-\frac{\alpha}{2}, N-1}$ is taken as 2.776. A mean change resulting in $\alpha = 0.05$, is considered to be significant.

Specific emission calculations

All the emissions measured were converted to brake specific emissions using the brake specific emissions in g/kWh calculated by using the expression.

$$GASx = \sum_{i=1}^{i=n} MGASx \,.\, WFi \;/\; \sum_{i=1}^{i=n} Pi \,.\, WFi$$

GASx is the brake specific emission values. Where WFi, is the Weighting coefficient, Pi is the brake power and MGASx is the exhaust gas mass flow.

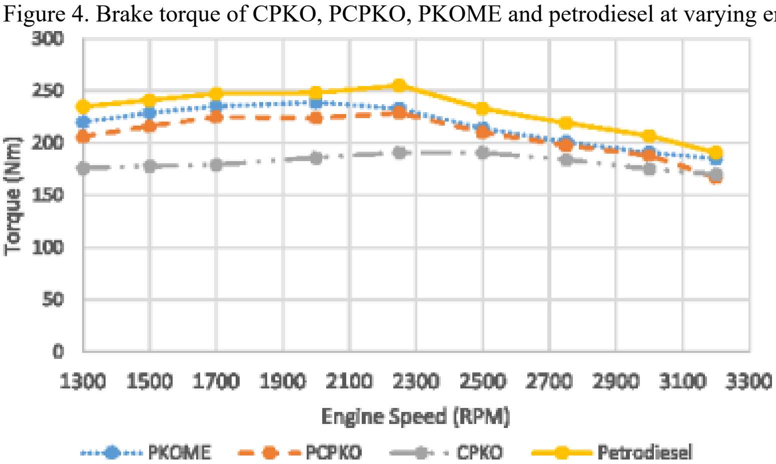
Results

Engine performance and emissions of crude palm kernel oil (CPKO), preheated palm kernel oil (PCPKO), palm kernel oil methyl ester (PKOME) in comparison with petrodiesel are discussed in this section. It is noticeable in Table 1 that, preheating the crude palm kernel oil reduced the viscosity by at least 59%. Transesterification of CPKO to PKOME further reduces it by 81% giving credence to the good performance of PKOME. The heating value was also improved significantly though cetane value did reduce through the transesterification process. It is worth mentioning that the The engine did not overheat throughout the entire experiment.

Brake torque

The graph of brake torque of PKOME, PCPKO, CPKO and petrodiesel is shown in Figure 4, below. Petrodiesel torque was higher than all the palm kernel oil fuels at all engine speeds taken. The primary reason is that the heating value of petrodiesel was higher than all the other fuels [26].

Figure 4. Brake torque of CPKO, PCPKO, PKOME and petrodiesel at varying engine speeds.

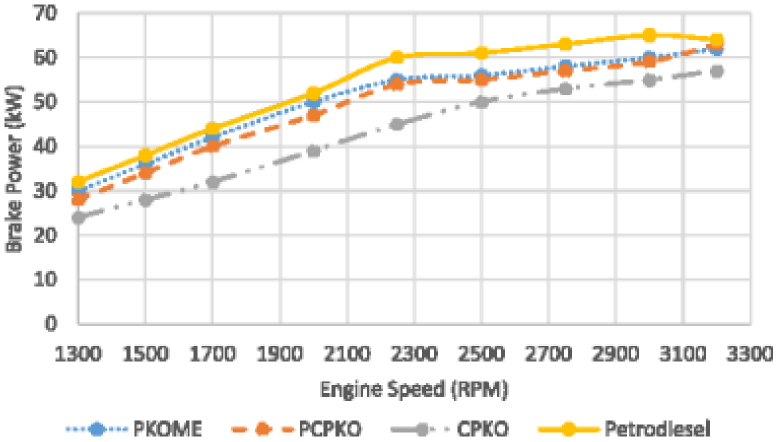


Hydrocarbons are mainly responsible for the energy content of a fuel. Petrodiesel has more hydrocarbons as compared to palm kernel oil. Mostly vegetable oils have lesser hydrocarbons due to their oxygen content which account for at least 10% of fuel [27]. This implies more palm kernel oil fuel will have to be injected to obtain the same performance as petrodiesel. The fuel with the next highest torque was PKOME, a palm kernel oil biodiesel. Apparently, the transesterification does increase the energy content of the fuel. Preheating the crude palm kernel oil also did improve the torque by 14%. Conversion of the crude vegetable oil to biodiesel improved the torque by 19% on the average.

Brake power

Once again due to high calorific value and low kinematic viscosity, petrodiesel recorded the highest average brake power of 53 kW compared to PKOME, PCPKO, CPKO which obtained brake power of 50 kW, 48 kW and 42 kW, respectively. The high viscosity of CPKO and its low calorific value accounts for its poor performance in terms of brake power (Figure 5).

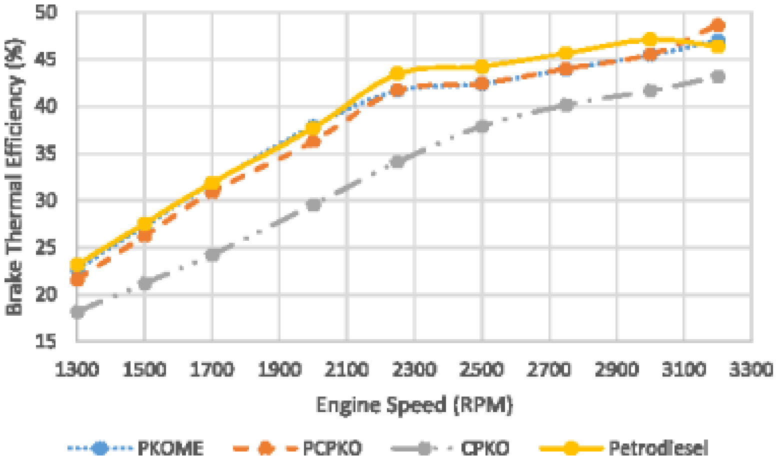
Figure 5. Brake power pattern with increasing engine speed.



Brake thermal efficiency

The maximum thermal efficiency of all the fuels were measured at the highest engine speed of 3200 rpm. The ratio of the brake power developed by the engine and the energy released per unit time due to complete combustion of the fuel is what is referred to as the brake thermal efficiency. At lower engine speeds air intake is slow and not sufficient for combustion but at a high speed, air is ingested at a higher rate aiding performance. It is seen from Figure 6, that at an average of 37.4%, PCPKO thermal efficiency exceeded that of CPKO by 16%. This is attributed chiefly to the lower viscosity of PCPKO.

Figure 6. Brake thermal efficiency pattern with increasing engine speed.

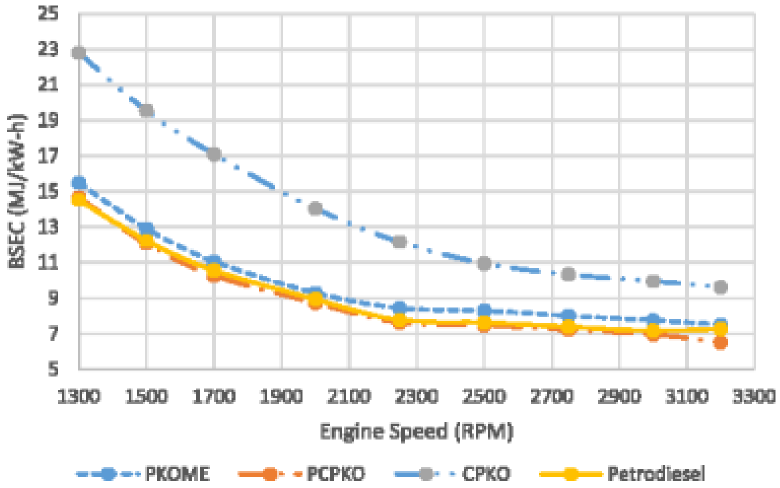


Brake specific energy consumption (BSEC)

BSEC is used to compare the efficiency of energy consumption of fuels. It is a better parameter compared to brake specific fuel consumption (BSFC) in analyzing the engine performance with different calorific values. Brake specific fuel consumption is the quantity of fuel for developing a unit power in a unit time. Only the effect of fuel density is considered in BSFC measurement. But when considering fuels of varying densities and calorific values it is better to consider BSEC above BSFC.

A measure of the BSEC at increasing engine speed is seen in Figure 7, below. The fuel consumption is high for all the fuels measured at low engine speeds but this reduces as the engine speed increases.

Figure 7. BSEC with engine speed.

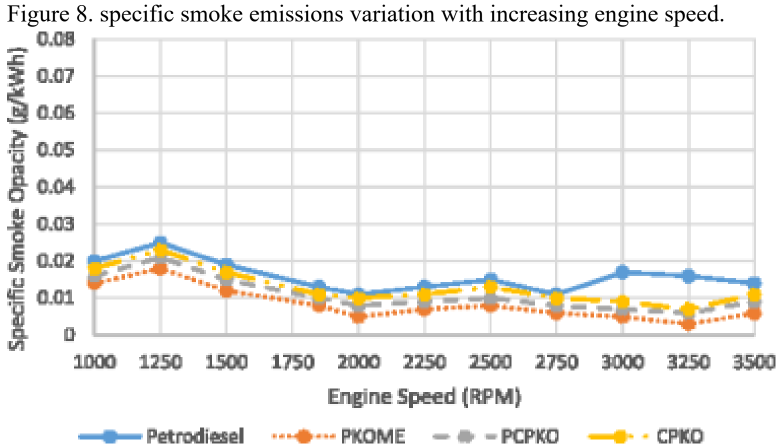


The lower the fuel consumption there is the better it is the better it is. The mean BSEC of PCPKO was found to be the best at 9.05 MJ/kW-h compared to petrodiesel, PKOME and CPKO at 9.26 MJ/kW-h, 9.85 MJ/kW-h and 14.05 MJ/kW-h, respectively. The BSEC of PCPKO was 2.3% lower petrodiesel. Preheating the fuel may have increased the in-cylinder temperature resulting in better atomization of the fuel [28]. Kinematic viscosity played the major role for the high BSEC of CPKO resulting in poor atomization.

Smoke

Hydrogen and carbon atoms are the main energy producing elements of petroleum and vegetable oils. Smoke and soot emissions are caused by incomplete combustions of carbon [29]. It has already been established that petrodiesel contains more hydrocarbons than vegetable oils leading to high smoke emissions when petrodiesel is used at all engine speeds (Figure 8).

Figure 8. specific smoke emissions variation with increasing engine speed.

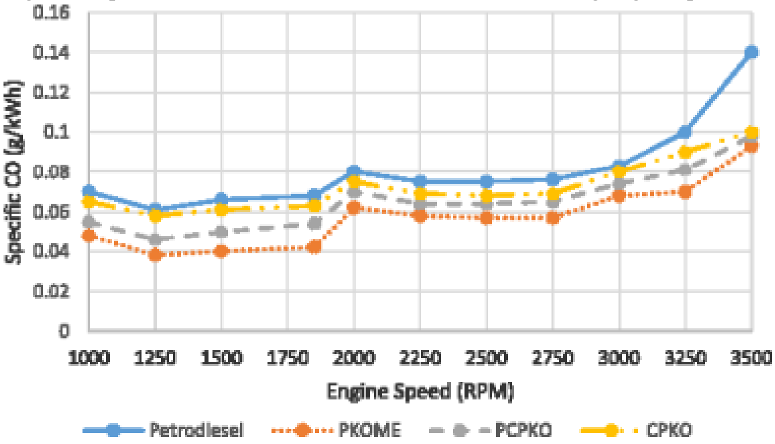


The higher oxygen content of vegetable oils and biodiesel is also another reason the palm kernel oil fuels recorded lesser smoke emissions. The oxygen content aids better atomization which is a prerequisite to a more complete combustion. Preheating the crude palm kernel oil contributed to less smoke emissions as PCPKO emissions were 18% less than CPKO.

Specific carbon monoxide (CO)

In Figure 9, the carbon monoxide emissions are shown for all fuels over a period of increasing engine speed. The CO emissions of petrodiesel is seen to be higher than all the palm kernel oil fuels at all engine speeds. On the average, petrodiesel CO emissions were found to be 41% higher than PKOME, 24% higher than PCPKO and 13% higher than CPKO.

Figure 9. Specific carbon monoxide formation with increasing engine speed.

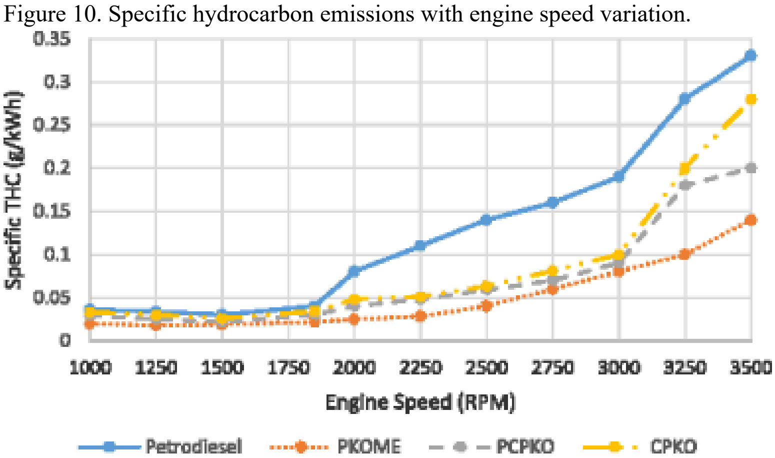


The high combustion efficiency of the palm kernel oils compared to petrodiesel is as a result of their oxygen rich content. Reducing the viscosity by preheating the crude palm kernel oil did reduce CO emissions by at least 10% while transesterification of the crude palm kernel oil into biodiesel, PKOME reduced the CO emissions by 21%. The lower emissions of PKOME is as a result of low viscosity preventing locally rich mixtures from forming [30]. The emissions of carbon monoxide are aided by poor atomization leading to incomplete combustion.

Specific total hydrocarbon emissions

Specific total hydrocarbon (THC) emissions are shown in Figure 10, below. The emissions at low speeds were not very obvious for all fuels. However, as the engine speeds increased the deviations are clearly seen especially for petrodiesel. Petrodiesel THC emissions were at least 159% more than any of the palm kernel oil fuels. Incomplete combustion as a result of poor atomization is the cause of THC emissions. The oxygen content of vegetable oils facilitates a better combustion leading to lesser THC emissions [31].

Figure 10. Specific hydrocarbon emissions with engine speed variation.

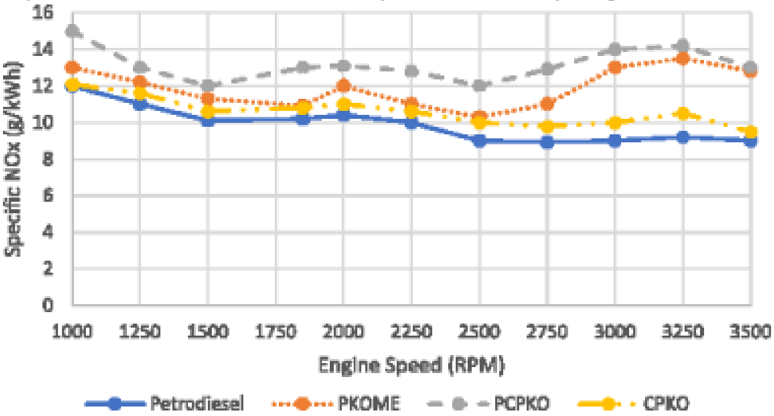


On the other hand, PCPKO emissions were 16% lower than CPKO for a different reason and mainly because of a lower viscosity of PCPKO. It is notable that as the engine speed increased emissions for all the fuels measured increased as well. This is due to lack of oxygen during combustion at higher engine speeds.

Specific oxides of nitrogen (NOx)

Oxides of Nitrogen (NOx) are not desirable emission products because they contribute immensely to the formation of smog, acid rain and depletion of the ozone layer. The graph of NOx emissions is shown in Figure 11, for all the fuels tested. None of the vegetable oil NOx emissions were better than petrodiesel. PCPKO produced much higher NOx emissions compared with unheated CPKO. This is attributed to the elevated heat addition to PCPKO since NOx formation is aided by high temperatures [28].

Figure 11. Emissions of oxides of nitrogen at different engine speeds.



Average emissions for all the fuels were 9.8 g/kWh for petrodiesel, 11.9 g/kWh for PKOME, 13.1 g/kWh for PCPKO and 10.5 g/kWh for CPKO. The highest emissions of NOx came from PCPKO which recorded 46% more emissions than CPKO. Addition of additives have been reported to be beneficial to NOx reduction with biodiesel use. NOx control strategies that have been discouraged with petrodiesel use due to Sulphur content can be used with biodiesel since biodiesel does not contain Sulphur.

Conclusion

The investigation into the performance and emissions of crude palm kernel oil (CPKO), preheated crude palm kernel oil (PCPKO), palm kernel oil methyl ester (PKOME) and petroleum diesel (petrodiesel) has been successfully completed. The following are the conclusions drawn from the work. Several advantages of preheating crude palm kernel oil before engine run were discovered. Another method of using coolant exiting the diesel engine to preheat the CPKO was very successful. Preheating the crude palm kernel oil reduced the viscosity by 59%. The procedure did not hinder the rate of cooling of the engine. Preheating also played an important role of improving the torque PCPKO by 14%. Since preheating reduced the viscosity, it played an important role in ensuring a more efficient atomization. Preheating crude palm kernel oil using the coolant improve thermal efficiency and THC emissions by 16% while smoke emissions reduced by 18%. This is attributed chiefly to the lower viscosity. Reducing the viscosity by preheating the crude palm kernel oil did reduce CO emissions by at least 10% while transesterification of the crude palm kernel oil into biodiesel, PKOME, reduced the CO emissions by 21%. It can be concluded that except for Oxides of Nitrogen, all other emissions such as CO, THC and specific smoke emission decreased when crude palm kernel oil was preheated using engine coolant.

Disclosure statement

No potential conflict of interest was reported by the authors.[AQ3]

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