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Effect of POME Additive in Algae-Diesel Fuel Blends on Fuel Consumptions and Emissions Characteristics of a Single Diesel Engine

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ABSTRACT

In the present investigation, the effects of Palm Oil Methyl Esters (POME) additives on fuel consumptions and exhaust emissions of a single-cylinder diesel engine fueled with algae-diesel fuel blends were studied. Five fuel blends were prepared based on volume percentages which are D100 (diesel fuel), 2.5AO97.5D (2.5% algae oil, 97.5% diesel fuel), 2.5POME2.5AO95D (2.5% POME, 2.5% algae oil, 97.5% diesel fuel), 3.5POME2.5AO94D and 4.5POME2.5AO93D. Next, fuel properties which are density, kinematic viscosity, and calorific value of all the blended fuels, were measured and analyzed. Engine tests were conducted on a single-cylinder diesel engine at a constant engine speed of 1500 rpm at various engine loads. The brake specific fuel consumption (BSFC), exhaust emissions of oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) were analyzed together during the experimental work. The obtained results for BSFC show that all fuel blends decreased with increasing engine load. The results obtained revealed that NO_X and CO_2 emissions increase, whereas CO emissions decrease with increasing engine load. The present work suggests 4.5POME2.5AO93D algae-diesel

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fuel blends with POME additive as a suitable eco-friendly alternative fuel as it gives better emission results compared to other fuel blends.

Keywords: Algae-diesel blends, biodiesel fuels, diesel engine, exhaust emissions, POME additive

INTRODUCTION

In these present days, the world demand for fossil fuels is surprisingly increased with the growing rate of industrialization. Because of that, fossil fuels resources are getting depleted in recent decades. People nowadays also notice that the heavy use of fossil fuels also causes environmental degradation. Thus, researchers grow their interest in alternative fuels to fulfill the energy demand by the whole world. In this context, biodiesel is the best available source of energy to satisfy world demand as it possesses a sustainable characteristic due to its renewable nature and positive environmental impact (Basha et al., 2009; Chauhan et al., 2012). Biodiesel fuels are also known as an alternative fuel that can reduce chemical emissions compared to fossil fuels which also depends on some engine specifications. When biodiesel fuels are blended with diesel, they can be used for a diesel engine without any modification as it presents almost similar traits to diesel fuels (Lapuerta et al., 2008). As reported by Lapuerta et al. (2008), biodiesel possesses a lower heating value when compared to diesel fuels, and this led to similar engine efficiency to diesel fuels if the fuel consumption is much higher. Moreover, biodiesel has a lower viscosity and shorter ignition delay when vegetable oil is blended with diesel fuels. In a paper prepared by de Almeida et al. (2002), biodiesel is said to have no sulfur content, which in the long run can reduce sulfate emission. It means that the sulfuric acid in our environment will be reduced and thus, helping to reduce toxic emissions being released into our atmosphere.

In the automotive industry, various types of biodiesel have been introduced, such as biodiesel from apricot seed kernel oil methyl ester, soybean crude oil, waste edible oil, and sesame oil methyl esters. Numerous research also has been made on algae oil to find its compatibility with diesel fuels (Demirbaş, 2008; Demirbas & Demirbas, 2011; Haik et al., 2011). Algae is known as a rapidly growing rate type of plant which needs less energy to be consumed than it can be produced (Demirbas & Demirbas, 2011; Nautiyal et al., 2014). Algae oil can be extracted using two methods which are extraction and expeller. As algae hold a high amount of glycerides, these methods will remove them and eventually increase the combustion rate of the diesel engine (Um & Kim, 2009). Consequently, algae oil blended with diesel fuels would probably produce less pollution to the environment compared to pure diesel fuels. Another possible biodiesel fuel is Palm Oil Methyl Esters (POME), non-toxic wastewater with chemical and physical properties almost similar to diesel fuel (Basha et al., 2009). However, POME produced high chemical oxygen demand (COD) and biochemical oxygen demand, which can cause violent pollution to the environment (Ndayishimiye & Tazerout, 2011). As the Malaysian palm oil industry has rapidly risen and contributed about 10.3% of the world's oils and fats production in 2007, it is demanded to be blended with diesel fuels to produce an alternative fuel replacing the existing fuels such as diesel fuels (Lam & Lee, 2011). It is due to its potential to possess renewable energy, which can contribute some advantages to the environment as well as the palm oil industry.

Although many studies have been conducted on algae oil and POME biodiesel, most of the studies only focused on its effect on diesel engine combustion, performance, and exhaust emission of the biodiesel. Haik et al. (2011) studied the combustion of algae oil methyl ester (ME) in a diesel engine which used five (5) different fuels ratio; base diesel fuel, algae oil methyl ester (0.2), algae oil methyl ester (0.1), algae oil methyl ester blended with diesel at 50/50 ratio and raw algae oil. The study shows that the combustion pressure rise rate of algae oil ME fuels is the highest compared with the other five test fuel samples. However, it is slightly decreasing with engine speed due to turbulence. Hence, it can be concluded that algae oil ME fuels have a shorter ignition delay as the fuel ignites quickly once injected. Besides, a high combustion pressure rate has also been recorded in algae oil ME, with the maximum pressure in the cycle also increasing, leading to increasing the piston resistance and reducing the output work and load. Other research has been done on the performance, combustion, and emissions characteristics of algae-diesel blends (Lam & Lee, 2011). The results showed that the fuel consumption of all fuel types decreased at increasing engine loads even at different injection timings. It is because the engine consumes more fuel as the engine loads increase. It is known that there is more oxygen content in biodiesel that helps for better combustion. The carbon monoxide (CO) emission for all fuels increases, but diesel has much lower CO emission compared to algae-diesel blends. The high oxygen content in biodiesel explains the situation as it leaves some unburnt hydrocarbons (HC). Similarly, the oxides of nitrogen (NO_x) emissions for biodiesel are higher than diesel even though both fuels have an increasing trend along with increasing engine loads. The high oxygen content and high combustion temperature are the reason for the formation of NOx emission.

Besides algae oil, POME blends with diesel fuel are also able to give better results in terms of the performance and emissions of a diesel engine. Mofijur et al. (2014) evaluated the performance and emissions characteristics of palm oil biodiesel in a diesel engine. The test was undergone at different engine speeds. Due to high calorific values and viscosities, it is found that the brake power (BP) of palm biodiesel is lower compared to pure diesel fuel. In terms of fuel consumption, biodiesel exhibits higher fuel consumption due to its high density and viscosity. Like other biodiesels, palm biodiesel is found to have lower CO and HC emissions. Biodiesel has high oxygen content, contributing to faster combustion than pure diesel fuel.

However, the carbon dioxide (CO_2) and NO_x for palm biodiesel is higher as it contains more unsaturated fatty acids, which contributes to high adiabatic flame temperature to the blend. In Brazil, a group of researchers has conducted an experiment on the performance of a diesel generator using palm oil (Jayaprabakar & Karthikeyan, 2014). The study showed that the exhaust gas temperature of palm oil increased with increasing charge. It happens due to high ignition delay, which delays the combustion process and thus, increases the exhaust gas temperature. For fuel consumption, palm oil has slightly higher fuel consumption compared to diesel fuel. The lower calorific value and higher density of palm oil contribute to larger mass fuel flow in the injection pump. It means that more palm oil is needed to run the diesel generator. In terms of emissions, the CO emission of palm oil is higher than diesel fuel due to its high viscosity. It causes more CO emissions to be released during the combustion process. The NO_x emission for both fuels increased with increasing charge, mainly caused by the increase of combustion temperature. Research has stated that this happens because NOx emission relies on engine speed and engine load (de Almeida et al., 2002). Another reason for this situation is that the turbulence intensity in the combustion chamber is increased, which eventually affects the air-mixture process.

Based on the literature that has been made, algae oil did prove its utility, especially in the transportation sector, due to its high efficiency compared to existing pure diesel (Graboski & McCormick, 1998). Moreover, algae oil also promotes almost similar power output to pure diesel fuels, which holds promise as an alternative fuel for diesel engines. However, a study conducted shows that biodiesel fuels used in diesel engines promote higher specific fuel consumption (Chauhan et al., 2012). Basha et al. (2009) conclude that the emission of oxides of nitrogen of biodiesel fuels is higher compared to pure diesel fuels as it contains more oxygen than pure diesel fuels. It is also known that the algae-diesel blends produce unstable biodiesel due to their high level of polyunsaturated fatty acids (Sharudin et al., 2019). In Malaysia, the rapid growth of palm oil plantations has become the driving factor towards biodiesel production (Demirbaş, 2008). According to research, the blend of 5% palm oil with diesel fuels in Malaysia creates new demand for palm oil, and thus, Malaysia is now keen on producing the POME to satisfy the standards (Lim & Teong, 2010). POME as biodiesel has a higher ignition quality because of its high molecular saturation (Sumathi et al., 2008). This trait may be a countermeasure to the disadvantage of the algae-diesel blends. By understanding the problem regarding algae-diesel blends, a new approach is made by adding POME into the algae-diesel fuel blend to overcome the problem. The properties such as density, kinematic viscosity, and calorific value will be investigated. In addition to that, the required brake specific fuel consumption (BSFC) and exhaust emissions; oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) will be analyzed during the experimental work of the engine testing.

METHODOLOGY

This section will discuss the preparation of the fuel samples, the methods used to identify the fuel properties, and the experimental setup to investigate the fuel consumptions and emission characteristics of adding POME into an algae-diesel fuel blend.

Preparation of Algae Oil

The preparation of algae oil will cover the overall process of producing algae oil. This process starts with collecting the algae oil from ponds, drying the algae, extracting algae oil, and evaporating ethanol from algae oil. The result from this process is collected in the form of liquid.

Collecting and Drying the Algae. The first step in producing the algae oil is to collect the raw algae. The algae were collected from a fishpond available in Sekolah Menengah Sains Tun Syed Sheh Shahabudin (SOKSEK). The algae were then dried using a vacuum pump to remove the water content left in the raw algae, as shown in Figure 1. All the dried algae were separated into small portions and packed into small sachets, which will be further dried in the universal oven at a temperature of 40^0C for 12 hours to remove all the water content in it. The purpose of this step is to make sure that the raw algae are completely dry to undergo the next process. All the drying process was conducted at the Chemical Engineering Laboratory in UiTM Pulau Pinang.

Extraction of Algae Oil. The small dry sachets of algae were then undergoing the extraction process using Super Critical Fluid Extraction (SCFE) in the Chemical Engineering Laboratory in UiTM Pulau Pinang. This method uses the carbon dioxide in liquified gas form as solvent and ethanol as the co-solvent. The setting configurations of the SCFE

Figure 1. Vacuum pump

machine were set up using the Process Suite software by setting the pressure to 300 bar, ethanol percentage to 10%, and temperature of 40℃. The process needs to wait until the chill temperature reaches 4℃. The full setup of the equipment is shown in Figure 2. The carbon dioxide cylinder valve was opened to ensure that the solvent entered the machine to assist the extraction process while ensuring a high co-solvent level in the 500 ml beaker. Next, about five to six small sachets of algae were filled into the extraction chamber at one time. During the process, the algae are pressurized and heated, where the carbon dioxide will act as the supercritical fluid to help the dried algae change into a liquid. The extraction process took an hour at one time. After an hour, the oil was slowly taken out from the recovery chamber, and the sachets in the extraction chamber were taken out before replacing them with the next batch. Overall, this process took almost 7 hours to convert all the dried algae into algae oil completely.

Figure 2. Super Critical Fluid Extraction (SCFE)

Evaporation of Ethanol from Algae Oil. In the previous process, the algae oil collected from the recovery chamber is mixed with ethanol as it is used as a co-solvent to help the rate of the extraction process. Therefore, an additional process of evaporating the ethanol from algae oil was conducted. This process was done in Chemical Engineering Laboratory in UiTM Pulau Pinang using a BUCHI Rotary Evaporator. The algae oil will be rotated in a thermostatic water bath to heat the algae oil so that there will be evaporation of ethanol. The first step to this process is by turning on the power of the machine, vacuum pump, vacuum controller chiller, and heating bath. The temperature of the water bath was set to 60℃, and the evaporating flask was filled with algae oil. It will be attached to the machine, as shown in Figure 3. Another smaller flask, called receiving flask, was attached to the ground glass joint while securing it with a clip to prevent falling. The speed of the evaporating rotation was set to 135 rpm using the rotation speed knob. By adjusting the manual lift knob, the vertical position of the evaporating flask was lowered until the water in the thermostatic water bath was enough to cover the level of the algae oil while leaving some space below the flask. Then, the vacuum pressure was set to 800 mbar, and the equipment was left until

Figure 3. The full set of BUCHI rotary evaporator

the ethanol had fully evaporated. The time taken for the evaporation process is about 5 to 10 minutes. The ethanol was evaporated into the receiving flask while the algae oil was left in the evaporating flask. Figure 4 presents the final product of algae oil.

Figure 4. The final product of algae oil

Preparation of the Blends. The preparation of the fuel blends was conducted after the algae oil was obtained. In this research, five fuel blends were prepared based on volume percentages, as shown in Table 1. The first fuel blend is pure diesel fuel, and it will be the reference to compare with the other fuel blends. The other four fuel blends contain 2.5% of algae oil each, while three out of those four contain 2.5%, 3.5%, and 4.5% of POME. Diesel fuel will be mixed first with algae oil to prepare the fuel blends. After that, POME will be added according to the proportion that has been set up. The blends were mixed using a magnetic

Table 1
The fuel blend ratio (vol.%)

Fuel Blend	Diesel (%)	Algae Oil (%)	POME (%)	Nomenclature
100% Diesel Fuel	100	0	0	D100
2.5% of Algae Oil + 97.5% Diesel Fuel	97.5	2.5	0	2.5AO97.5D
2.5% of POME + 2.5% of Algae Oil + 95% Diesel Fuel	95	2.5	2.5	2.5POME2.5AO95D
3.5% of POME + 2.5% of Algae Oil + 94% Diesel Fuel	94	2.5	3.5	3.5POME2.5AO94D
4.5% of POME + 2.5% of Algae Oil + 93% Diesel Fuel	93	2.5	4.5	4.5POME2.5AO93D

stirrer at a speed of 450 rpm and the time taken is 15 minutes for each fuel blend. The mixing process was done in the mixing chamber, and Figure 5 shows the stirring process using a magnetic stirrer. This process was conducted in Reservoir Laboratory, Faculty of Chemical Engineering in UiTM Shah Alam.

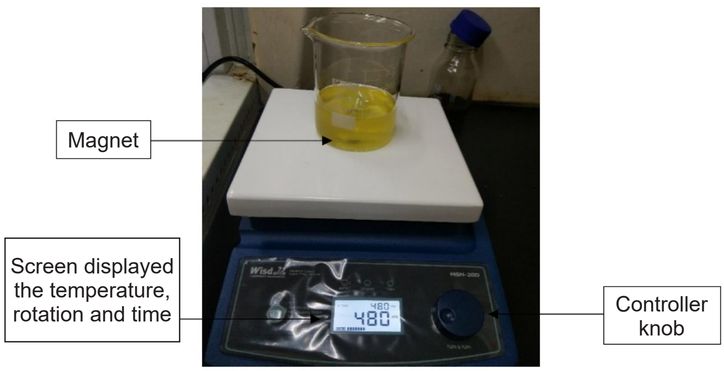

Figure 5. The magnetic stirrer

Characterization of Fuel Properties

The fuel properties that were identified are density, kinematic viscosity, and calorific value. The fuel properties identification process was conducted using suitable equipment following the test standards.

Density and Kinematic Viscosity. The density and kinematic viscosity were measured using American Standard Test Material (ASTM) standard. The identification of both properties is conducted at Engine and Tribology Laboratory at Department of Mechanical Engineering, Universiti Malaya (UM) using Stabinger Viscometer SVM3000. The viscometer needs to be set up before conducting any properties identification. The temperature needs to be set to 15°C according to ASTM D4052 to identify the density. The sample tube must be clear from any liquids from the previous experiment, and thus, acetone is injected through the hole. Acetone works as a cleaning agent for most of the equipment in a laboratory. After that, the vacuum is used to clear the sample tube from the acetone. Then, wait until the temperature rises to 15°C. A disposable syringe is used to introduce almost 2.5 ml of fuel blend from the hole. It has to be sure that no air bubbles are present to avoid difficulty getting the result. If any air bubbles are present, the sample tube needs to be emptied and refilled. Then, the start button is pressed. Wait for a while before the result is obtained. Next, acetone is used again to clean the tube and vacuum the tube to identify the other fuel blend. The waste in the sample tube will go to the waste container. The steps are repeated for the next fuel blends. Like density identification, the temperature needs to be 40°C according to ASTM D7042 for kinematic viscosity. The other steps are being repeated throughout the identification process. The overall process takes about an hour to complete. Figure 6 below shows the viscometer used during the identification process.

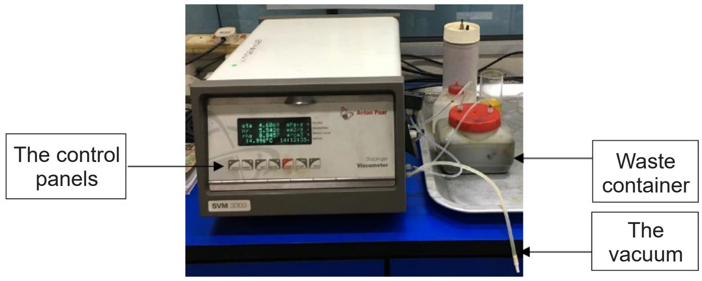

Figure 6. The Stabinger Viscometer SVM3000

Calorific Value. C200 Bomb Calorimeter is used to identify the calorific value, as shown in Figure 7. The test procedure was conducted in Instrumentation Laboratory II at the Faculty of Chemical Engineering, UiTM Shah Alam. The test was conducted in accordance with ASTM D240. The fuel blend was put in a crucible using a small pipette and was measured mass to almost 1g using analytical balance to start the procedure. The crucible is then placed in the bomb sample holder. An almost 5 cm thread was tied on the ignition lead wire of the bomb sample holder, and its other end needed to touch the fuel blend in the crucible. The bomb sample holder is then put in the bomb and closed the lid. Next, the bomb was attached to the lifting handle. The mass of the fuel blend was inserted using the instrument panel screen. Then, the OK button was pressed. The bomb was lowered into the fitted slot, and the calorimeter conducted the test. Around 20 minutes is needed for the bomb calorimeter to analyze the result. After it is done, the bomb will automatically be opened partially. Then it needs some time to cool down it is completely opened. The result is out on the instrument panel screen. Inside the bomb calorimeter, the ignition lead wire will cause the fuel blend to burn through the thread. Release the pressure in the bomb

Figure 7. C200 Bomb Calorimeter

by opening its lid. The crucible and bomb sample holder were washed and dried before conducting the process for the next fuel blend. The steps were repeated until the calorific value of all fuel blends was obtained.

Engine Setup

The engine setup procedure was conducted in Automotive Laboratory at the Faculty of Mechanical Engineering, UiTM Shah Alam. The diesel engine was coupled together with an eddy current dynamometer. All tests were performed on a fuel injection, four-cycle single-cylinder diesel engine from the Yanmar L70N6 series with the following specifications as shown in Table 2.

Table 2
The specification of Yanmar L70N6 series diesel engine

Parameters	Values
Type	Vertical cylinder, 4-cycle air-cooled diesel engine
No of cylinders	1
Bore x Stroke	0.078 m × 0.068 m
Combustion	Direct Injection
Maximum Output	4.9 kW at 3600 rpm

The schematic diagram for the overall setup of the engine is shown in Figure 8. The power supply panel was used to adjust the variation of engine load and speed of the engine. The control panel was used to monitor the engine load and speed as the needle that indicates the engine load and speed are easily fluctuates.

Exhaust Gas Analyzer. An exhaust gas analyzer shown in Figure 9 was used to analyze the exhaust emissions of every fuel blend with various engine loads. The exhaust gas

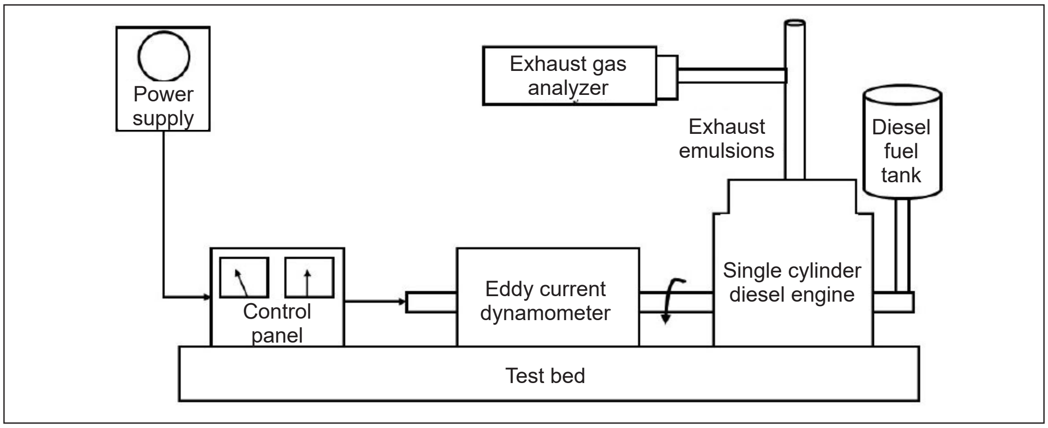

Figure 8. The schematic diagram of engine setup

Figure 9. Exhaust gas analyzer

analyzer used was from VARIO Plus Industrial, the MRU Air model. The exhaust gas analyzer and the system have been calibrated by suitable bottled span and zero calibration gases to obtain accurate data for the emissions. The exhaust emissions being analyzed are only CO, CO_2, and NO_x. Firstly, the grid power supply needs to connect the exhaust gas analyzer and power supply. Next, the sample gas inlet, heated hose, and T-Gas of the probe are connected to the exhaust gas analyzer. Then, the ON button is pressed. Before using the exhaust gas analyzer, it is allowed to run for 30 minutes to recharge. Make sure that the probe is not in contact directly with the opened fan. After that, the probe is inserted into the exhaust of the diesel engine. Together with the time taken and EGT, the results of those exhaust emissions were printed out. The data that needs to be collected for exhaust gas emissions is in percentage for CO_2 and parts per million (ppm) for NO_x and CO.

Engine Test Condition

The operating condition for the engine testing was performed at constant engine speed (1500 rpm) with increasing of engine load from 0 Nm until 6 Nm at an equal increment of 2Nm. The engine testing procedures were first started by warming up the engine with D100 and starting the gas analyzer to allow it to operate until it achieves optimum condition (constant engine temperature) before the experiment can be conducted. The gas analyzer was set up to ensure the receiver is pointed directly towards the incoming gas expelled from the machine, as shown in Figure 8. Next, the 2.5AO97.5D blends are fueled in the fuel tank up to replace D100 blends. The engine was left running with the blended fuels until it reached the steady-state condition. Then, all the required data for fuel consumption and exhaust emission will be collected. D100 blends were used as an intermediate fuel to flush out all the remaining blends, specifically in the fuel line system of the diesel engine to change to the next fuel blend. This method needed to be conducted to avoid the fuel blend mixing with another fuel blend, which could affect the result of the study. Finally, all the reading of the required data was repeated three times for each load of all blends to increase the accuracy and consistency of the obtained results.

RESULT AND DISCUSSION

This section explains the results and discussion of analyzing and discussing the recorded data. The results of fuel properties such as density, kinematic viscosity, and calorific value for all the fuel blends have been recorded and investigated. In addition to that, the required brake specific fuel consumption (BSFC) and exhaust emissions; oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) have also been recorded during the experimental work of the engine testing.

Fuel Properties

The density, kinematic viscosity, and calorific value of all fuel blends were examined and identified by referring to ASTM D4052, ASTM D7042, and ASTM D240, respectively. The physicochemical properties of all fuel blends, such as density, kinematic viscosity, and calorific value, were presented in Table 3. From the results obtained, the density and kinematic viscosity of all test blends are still within the test range limits. Compared with Title 40, Code of Federal Regulations, Part 1065.703, the fuel density range limits are between 0.840 g/cm^3 to 0.860 g/cm^3, while the fuel kinematic viscosity range limits are between 2.0 mm^2/s to 3.2 mm^2/s. The calorific value range limits are not stated in the regulation**.**

Table 3
The physicochemical properties of all fuel blends

Fuel Blend	Density (g/cm^3)	Calorific Value (kJ/kg)	Kinematic Viscosity (mm^2/s)
Algae Oil	0.9000	40000	3.7000
POME	0.8750	39900	4.9100
D100	0.8500	45500	2.6000
2.5AO97.5D	0.8453	45243	3.0027
2.5POME2.5AO95D	0.8452	43693	3.0326
3.5POME2.5AO94D	0.8462	44136	3.0089
4.5POME2.5AO93D	0.8466	44240	2.9985

Brake Specific Fuel Consumption (BSFC)

The brake-specific fuel consumption (BSFC) for all fuel blends decreases with increasing engine load, as shown in Figure 10. From the results, at engine load equals 0 Nm, there is no calculated BSFC. The BSFC is calculated using a formula while using the information gathered during the experimental procedure. Next, when the engine load is at 2 Nm, the BSFC of biodiesel fuel blends is lower than D100. The difference between D100 and 4.5POME2.5AO93D is 18.42%. It may be due to the engine condition where it gets hot faster as the engine load increase. At 6 Nm engine load, the fuels exhibit almost similar results. However, 4.5POME2.5AO93D with 558.41 g/kWHr of BSFC still is the lowest

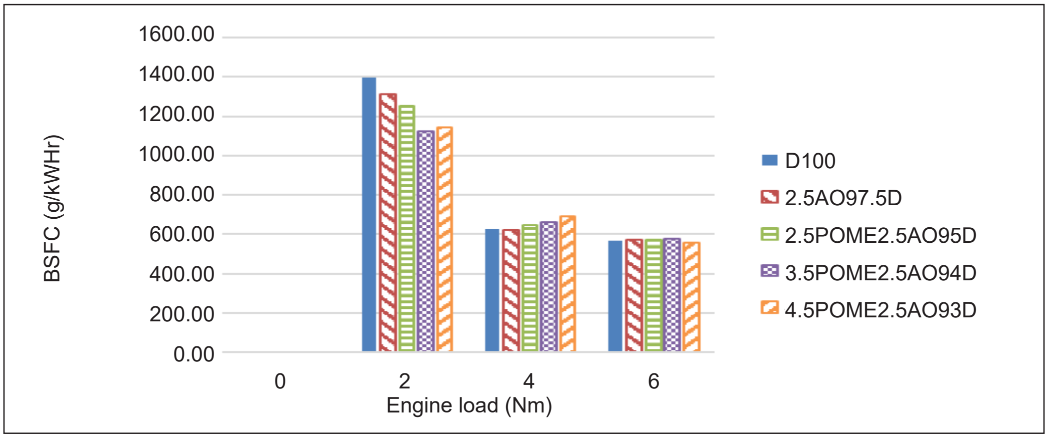

Figure 10. The BSFC Performance respected to engine load

among all five fuel blends, whereas 3.5POME2.5AO94D has the slightly higher value of BSFC at 570.37 g/kWHr.

Based on the result obtained, as the engine load increases, the BSFC will decrease because of the lower calorific value. It leads to less fuel discharge in the fuel injection pump, and therefore, lowers the BSFC (Chauhan et al., 2012). So, if fuel has a lower calorific value compared to diesel fuel, it will have a lower BSFC. Figure 10 showed that increasing POME proportion in a fuel blend decreased the BSFC. It may be explained regarding the increasing brake power as the engine load increases (Jayaprabakar & Karthikeyan, 2014).

Oxides of Nitrogen (NO_x)

Figure 11 represents the oxides of nitrogen (NOx) of all fuel blends. If the graph looks closely, the NOx for all fuel blends seems to increase along with increasing engine load. The engine load equals 0 Nm, 4.5POME2.5AO93D having the lowest NOx with 16.22%. D100 has the lowest NOx with 15.06% at 2 Nm of engine load and 17.11% at 6 Nm of engine load. While at engine load equals 4 Nm, 3.5POME2.5AO94D exhibits the lowest NOx at 15.15%. For engine load equals 0 Nm and 2 Nm, 2.5AO97.5D is the highest, 26.49% and 25.6%, respectively. However, at engine load equals 4 Nm and 6 Nm, 4.5POME2.5AO93D has the highest NOx, 26.34% and 23.38%, respectively. The percentage difference between the highest and lowest at engine load equals to 0 Nm is 9.93%, at 2 Nm is 10.54%, at 4 Nm is 11.19%, and at 6 Nm is 6.27%.

Based on Figure 11, it can be said that the NOx will increase along with increasing engine load. Overall, the fuel blends have higher NOx than pure diesel fuel. It might result from high oxygen content in the biodiesel fuel blends, which leads to improvement in the combustion (Gumus & Kasifoglu, 2010; Lim & Teong, 2010). Higher content of oxygen contributes to better combustion efficiency while increasing the temperature in the

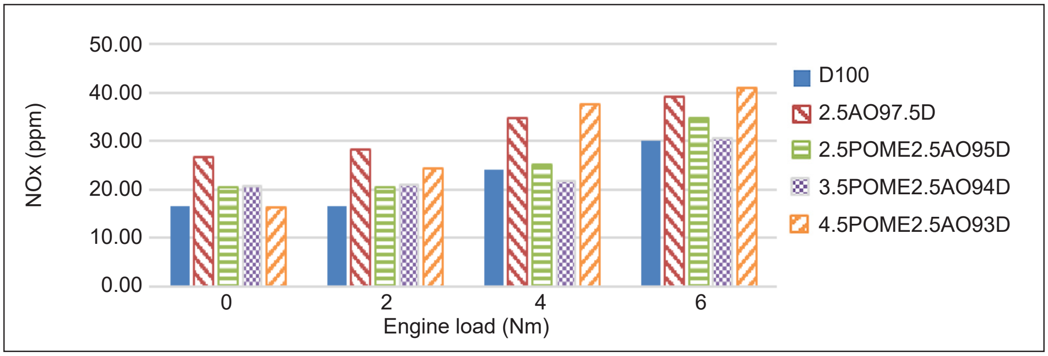

Figure 11. The NOx emission respected to engine load

combustion chamber (Adeniyi et al., 2018). Besides, the lower density of biodiesel fuel blends also could increase NOx emissions (Piloto-Rodríguez et al., 2017).

Carbon Monoxide (CO)

The result for CO emissions of all fuel blends was presented in Figure 12. Roughly, the result below shows a decreasing trend for all fuel blends. The percentage difference between maximum and minimum is 40.17%, 53%, 64.59%, and 53.52% when the engine load is 0 Nm, 2 Nm, 4 Nm, and 6 Nm, respectively. 4.5POME2.5AO93D maintains to be the lowest fuel blend that exhibits CO emissions from 0 Nm to 6 Nm of engine load. At engine load 0 Nm, 2.5AO97.5D and 2.5POME2.5AO95D have the highest value of CO emissions. When the engine loads are 2 Nm and 4 Nm, 2.5AO97.5D shows the highest CO emissions, while when engine load is 6 Nm, 2.5POME2.5AO95D is the highest.

According to previous research, the higher the percentage of biodiesel blends in the fuel, the lower the CO emissions because of the presence of oxygen that helps to complete combustion while converting the CO into CO_2 emissions (Adeniyi et al., 2018; Chauhan et al., 2012). In this case, the volume of POME is higher in 4.5POME2.5AO93D compared to

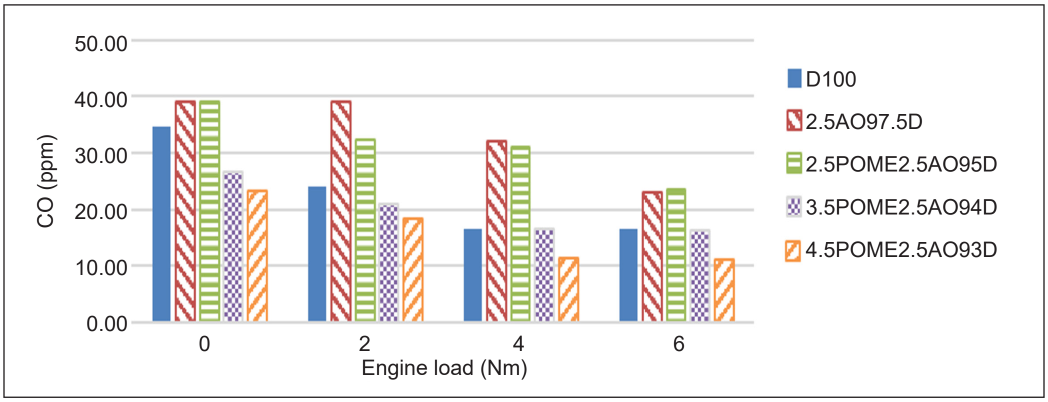

Figure 12. The CO emission respected to engine load

other fuel blends. As the oxygen content in biodiesel fuel blends is high, the carbon content is lower, contributing to incomplete combustion of hydrocarbons (HC). Thus, the engine temperature will be higher and lower the CO emissions (Piloto-Rodríguez et al., 2017).

Carbon Dioxide (CO_2)

Figure 13 displays the result for CO_2 emissions of all fuel blends and increasing engine load. Figure 13 clearly shows an increasing trend of CO_2 emissions as the engine load increase. There is not much difference between all fuel blends for each engine load. D100 exhibits the lowest CO_2 emissions from 0 Nm to 6 Nm of engine load except for 4 Nm, where 2.5POME2.5AO95D is the lowest. 2.5AO97.5D has the maximum CO_2 emission at 0 Nm and 2 Nm of engine load. 4.5POME2.5AO93D has the highest CO_2 emission at 4 Nm of engine load, whereas at 6 Nm, 3.5POME2.5AO94D is the highest. The percentage difference between the maximum and minimum is 17.91%, 17.39%, 27.5%, and 22.32% for engine load at 0 Nm, 2 Nm, 4 Nm, and 6 Nm, respectively.

From the result shown in Figure 13, the CO_2 emissions of D100 are lower than other fuel blends. This condition is related to the amount of oxygen content in biodiesel and diesel fuel. The higher the oxygen content in fuel, the carbon content will be relatively low (Adeniyi et al., 2018). The CO_2 emissions will increase if the engine load increases, indicating the complete combustion happened in the diesel engine. Not only that, but the high value of kinematic viscosity of the biodiesel fuel blends also helps in increasing the trend of CO_2 emissions, which contributes to increasing combustion rate (Chauhan et al., 2012).

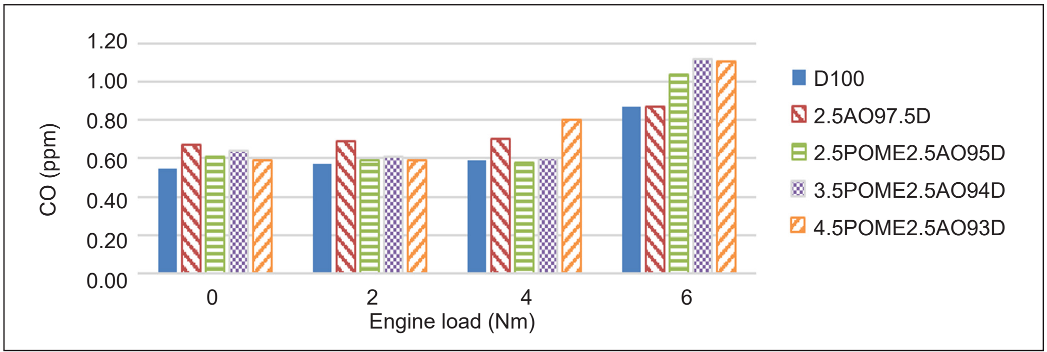

Figure 13. The CO_2 emission respected to engine load

CONCLUSION

The main purpose of this research is to evaluate the effect of adding POME into algae-diesel fuel blends properties and investigate the fuel consumption and emissions characteristics of adding POME into algae-diesel fuel blends. The conclusion of this study are as follows:

1. The BSFC for all blends decreased with increasing engine load. However, POME addition into algae-diesel blended fuels has lower BSFC compared to diesel fuel. It is due to the fewer calorific values of biodiesel fuel blends. This research shows that 4.5POME2.5AO93D has the lowest BSFC among fuel blends and the increased engine load.
2. The higher amount of POME in a fuel blend causes the NOx emission to be higher. The lower density of biodiesel contributes to an increase in NOx emission. Due to the high oxygen content in biodiesel, it improves the combustion efficiency of fuel. In this research, 2.5AO97.5D and 4.5POME2.5AO93D showed the highest NOx emission compared to all fuel blends.
3. The CO emission decreases with increasing engine load for all fuel blends. It can be observed that more biodiesel content in a fuel contributes to lower CO emissions. It is due to the presence of oxygen that helps to complete combustion while converting CO into CO_2 emissions. This research proves that more biodiesel content in fuel reduces CO emissions.
4. The CO_2 emission of all fuel blends increases from an engine load of 0 Nm to 6 Nm. The biodiesel fuel blends released higher CO_2 emissions compared to diesel fuel. It contains more oxygen components which relatively makes the carbon content in the biodiesel to be low. In this research, 4.5POME2.5AO93D released the highest CO_2 emission compared to other biodiesel fuels blends.

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