



COMPARATIVE STUDY OF THE PERFORMANCE AND EXHAUST GAS EMISSIONS OF BIODIESELS DERIVED FROM THREE DIFFERENT FEEDSTOCKS WITH DIESEL ON MARINE AUXILIARY DIESEL ENGINE

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ABSTRACT

In order to reduce the global environmental impact from internal combustion engines in terms of emissions particularly in the production of greenhouse gases (GHG), one of the most promising ways is the use of bio-derived fuels. To this purpose, the utilisation of biodiesel (pure or in blends) in diesel engines is already quite common in some countries due to its properties comprehensively similar to petro-diesel. The major positive effect not only intrinsic to the significant reduction in CO₂ emission but reducing CO, HC and smoke emissions, even though it typically causes an appreciable increase in NO_x emissions. However, the use of the biodiesel has some limitation due to efficiency drops and long term complications to the engine. Therefore, this study aims to examine the effects of different biodiesel blends on engine performance and exhaust gas emissions of marine auxiliary diesel engine and recommends bio-fuel that optimising the engine performance and lower emissions. This study found there has been an increment in engine performance specifically on torque, brake power, brake thermal efficiency (BTE) and brake mean effective pressure (BMEP) along with lower and better in brake specific fuel consumption (BSFC) crude palm biodiesel oil (CPO) and jatropha curcas biodiesel oil (JCO) blended fuels, while decreased in engine performance associated with higher BSFC by waste cooking biodiesel oil (WCO) blends compared to neat petroleum diesel. Aside, the reductions of CO, CO₂ and HC by CPO; slightly increment in CO₂, NO_x and HC by JCO and acceptable CO₂, CO and NO_x gas productions by WCO has been discovered. Conclusion can be made is biodiesel blend fuels is operable in diesel engines without engine alterations as well as advantageous for exhaust emission reductions yet beneficial to the environmental sustainability.

Keywords: biodiesel, diesel engine, exhaust emission, engine performance.

INTRODUCTION

Diesel engines provide important transportation and machineries power sources which are receiving extra attention due to their relative operating efficiency. Higher operating efficiencies lead to reduced fuel consumption and exhaust gas emissions. However, the lessening of other exhaust emissions to meet new emissions standards remains a challenge. Modifications of engine and developments of exhaust after treatment are making progress toward this goal, but additional effort is being focused on potential improvements and alternative for diesel fuel. In recent years, many researches have been carried out to evaluate the exhaust gas emissions and performance characteristics as well as the advantages of biodiesel. Some factors, such as environmental concerns and a continuing rise in crude oil prices, have focused more efforts on biodiesel use (Khalid, Mudin, Jaat, *et al.*, 2014; Kinoshita, Myo, & Hamasaki, 2006). The used of bio-fuel in diesel engine offered good potential to be used as an alternative fuel that can reduce the exhaust gas emission especially carbon dioxide (CO₂) from the internal combustion engine (Khalid, Nursal, Tajuddin, & Hadi, 2016).

This study used biodiesel fuels which produced from crude palm oil (CPO), Jatropha oil (JCO) and waste cooking oil (WCO) feedstocks. Biofuels based on vegetable oils offer the advantage being a sustainable, annually renewable source of fuels and received a lot of

attention nowadays. The selection of this vegetable oil instead of animal fat is prior to the great fuel properties such as flash point and acid value that comparable to the petroleum-diesel fuel (Hossein, Ashnani, Johari, & Hashim, 2014). The capability of CPO to be used as biodiesel due to the higher level of molecular saturation of it contains that leads to a higher ignition quality in compression ignition (CI) engine. Though, this also leads to a higher cloud point that worse to use in cold weather. As JCO is found to contain as much as 34 wt.% of saturated fatty acids, Jatropha biodiesel fuel is predicted to exhibit poor operability at low temperature (Lim & Teong, 2010). Aside, the key issue in using waste cooking oil based fuel is oxidation stability, stoichiometric point, bio-fuel composition, antioxidants on the degradation and much oxygen with comparing to conventional diesel fuel (Khalid, Anuar, Ishak, *et al.*, 2014). Even though the application of WCO in the diesel engines offer cheaper fuel in term of cost but it also generates higher emissions as compared to petroleum based diesel in which may contribute to the formation of acid rain (Demirbas, 2008)? Furthermore, the important issue is the emission exhausted caused by biodiesel is required to meet the latest stringent emission regulations. Hence, the improvement of emissions released from biodiesel is immediately required to meet the strict regulations. In other hands, the implementation of boost pressure, swirl velocity and injection pressure has a great effect on the mixture



formation, turbulence, ignition delay, ambient density and ambient pressure yet subsequently affecting the flame propagation, combustion characteristics as well as better emissions elements.

As summary, most of biodiesel fuels have faced problems where the fuels are not operating effectively in cold weather and some of them may lead to the increasing of emissions as well as fuel consumption due to instable fuel properties or inappropriate blending proportion. Therefore, this research works expected to provide knowledge of the effects on performance as well as emission characteristics.

BIODIESEL FUELS

Biodiesel is a clean-burning fuel produced from grease, vegetable oils, or animal fats. The quality of biodiesel depends upon the feedstock quality, chemical composition of feedstock, production process, storage and handling process (Abedin, Masjuki, Kalam, Sanjid *et al.*, 2014). Biodiesel is produced by transesterification of oils with short-chain alcohols or by the esterification of fatty acids. The transesterification reaction consists of transforming triglycerides into fatty acid alkyl esters, in the presence of an alcohol, such as methanol or ethanol, and a catalyst, such as an alkali or acid, with glycerol as a by-product. Since biodiesel is made entirely from vegetable oil or animal fats, it is renewable and biodegradable. The majority of biodiesel today is produced by alkali-catalysed transesterification with methanol, which results in a relatively short reaction time. However, the vegetable oil and alcohol must be substantially anhydrous and have a low free fatty acid (FFA) content, because the presence of water or FFA or both may promote soap formation (Vasudevan & Briggs, 2008).

OVERVIEW OF THREE DIFFERENT BIODIESEL FEEDSTOCKS

The increasing importance of sustainability in energy production has led to a global commitment to the use of fuels derived from renewable biological sources, such as biodiesel produced from plant crops. A range of feedstocks are used globally, including palm, rapeseed, cotton seed, soy, jatropha, sunflower, animal fat, waste cooking oil and many more. In this research, the biodiesel fuels were produced from oil palm, jatropha curcas and waste cooking oil feedstocks.

Crude palm oil

The oil palm fruits feedstocks for producing crude palm oil (CPO) is botanical classification as *Elaeis guineensis* and native to the West Africa where it was growing wild and later developed into an agricultural crop, widely in south East Asia. The oil palm tree contributes in releasing a large quantity of O₂ to the atmosphere than other annual crops and absorbed a lot CO₂ during photosynthesis. The economics life span of oil palm is 25-30 years of total 200 years (Lim & Teong, 2010; Ong, Mahlia, Masjuki, & Norhasyima, 2011). The fleshy orange reddish coloured fruits grow in large and tight female

bunches each one weight as much as 10-40 kg and contain up to 2000 fruitlets as shown in Figure-1. The fruitlet consists of a fibrous mesocarp layer and the endocarp (shell) containing the kernel which contains oil and carbohydrate (Ong *et al.*, 2011). Oil palm plants are well-known with highest yield of vegetable oil. It produce on average about 4-5 tonnes of oil/hectare annually (Lim & Teong, 2010; Ong *et al.*, 2011).



Figure-1. Oil palm tree and fruits.

Jatropha curcas oil

Jatropha Curcas is a drought-resistant tree belongs to the Euphorbiaceae family, which is cultivated in Central and South America, South-east Asia, India and Africa. It is easy to establish, grows almost everywhere even on gravelly, sandy and saline soils. It produces seeds after 12 months, can live 30-50 years and reaches its maximum productivity by 5 years with a high oil content of about 37% or more. The oil from the seeds has valuable properties such as a low acidity, good stability as compared to soybean oil, low viscosity as compared to castor oil and better cold properties as compared to palm oil. Besides, Jatropha Curcas oil (JCO) has higher a cetane number compared to diesel which makes it a good alternative fuel with no modifications required in the engine (Atabani, Silitonga, Ong, Mahlia, & Masjuki, 2013; Koh, Idaty, & Ghazi, 2011; Ong *et al.*, 2011). The optimum combination for reducing the free fatty acids (FFA) of Jatropha curcas oil ensuring an average yield of biodiesel is more than 99% (Vasudevan & Briggs, 2008). Fresh Jatropha is a slow drying, odourless and colourless oil and become yellow after aging as shown in Figure-2.



Figure-2. Jatropha curcas plant and seed.

Waste cooking oil

Waste cooking oil (WCO) also known as restaurant waste oil refers to oil that has been hydrogenated after cooking. Cooking oils, used for frying food, have a limited life in food production due to their contamination with debris from food and due to fatty acids



formation. As a result, waste cooking oil can be seen as a “near to waste” by-product of food production industry (Rosca *et al.*, 2005). WCO offers economic advantages and significant potential as an alternative low cost biodiesel because it does not need production cost compared to other types of biodiesel. By using of WCO as biodiesel, it can solve the environment pollution problems either to avoid WCO dumped in the river or to avoid the purification of the main drainage water system water (Atabani *et al.*, 2013; Demirbas, 2008; Khalid, Mudin, *et al.*, 2014; Payri, Macián, Arrègle, Tormos, & Martínez, 2005). However, other issues arise due to kinematic viscosity of the WCO is ten times higher than diesel, and it is estimated that the spray characteristics get significantly worse with increasing WCO addition (Yoshimoto, Onodera, & Tamaki, 1999). WCO is known as yellow greases as viewed in Figure-3, even the free fatty acids (FFA) level is less than 15 wt.%, due to greatest abundance it can be considered similar to brown greases which FFA content is in excess of 15 wt.%.



Figure-3. Yellow grease content in used frying/waste cooking oil (WCO).

COMPREHENSIVE RESEARCH METHODOLOGY

Production of biodiesel in pilot plant

Firstly, the pure biodiesel fuels were produced from selected feedstocks. Production of biodiesel used in the study was done in biodiesel pilot plant located in Universiti Tun Hussein Onn Malaysia. The appropriate biodiesel is produced by the chemical transformation of

feedstocks either vegetable oils or animal fats into the corresponding long-chain fatty acid alkyl esters, known as transesterification. The transesterification of triglycerides in oil with a lower alcohol in the presence of an acidic or a basic catalyst purposely to reduce the viscosity of vegetable oil. The basic transesterification reaction process is shown in Figure-4.

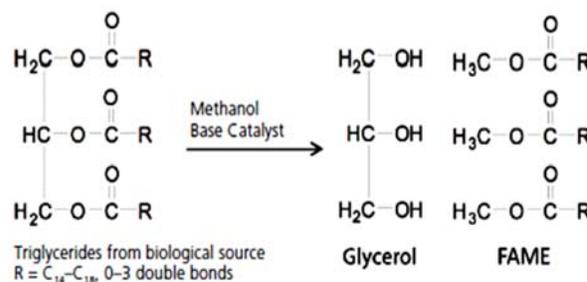


Figure-4. Reaction scheme for the production of biodiesel.

The biodiesel production begins with the first module for crude oil pre-treatment which converts crude vegetable oil into bleached oil, the second one for refining and separating which converts and processes the bleached oil into the end product of biodiesel that meets standard specifications. In the pre-treatment module, the process begins with degumming when the crude oil either crude palm oil, crude jatropha curcas oil or used/waste cooking oil is treated with phosphoric acid to remove natural gums, and followed by bleaching with activated earth under vacuum to remove the colouring matters as well as to adsorb any metal ions content. Other impurities such as dirt and solid particles are removed using a bleaching earth filter. The purpose of pre-treatment is to prepare the raw materials quality to be fit for the second module. The product of this module is the refined bleached oil. The subsequent process is esterification and transesterification of the bleached oil with methanol under the presence of acid and base catalyst, respectively. The esterification process converts free fatty acids containing in the bleached oil to methyl esters under mild conditions. This reaction product is then transferred into the transesterification reactor with methanol to form fatty acid methyl ester (FAME) or biodiesel. The methyl esters are then washed, filtered, and vacuum dried before sending to the storage (Sani, Hasnan, Md Yusof, & Baba, 2013; Sani & Hasnan, 2008).

Preparation of biodiesel blends fuels

Biodiesel produced in pilot plant was then undergo blending process with neat diesel. Three types of biodiesel blends which consist of crude palm oil (CPO), jatropha curcas oil (JCO) and waste cooking oil (WCO) were prepared for this experiment. The purified biodiesel from the three different feedstocks are blended with standard diesel (DSL) in 5% v/v blending concentrations which means by 95% diesel mixed with 5% biodiesel through specific procedure. These blended fuels are



denoted as CPO for crude palm biodiesel blends fuel, while JCO is for jatropha curcas biodiesel blends fuel and WCO is for waste cooking biodiesel blends fuel respectively. The petroleum-diesel fuel (DSL) with grade IV i.e Euro 4 diesel rated is tested along with the biodiesel blends fuel and nominated as a reference standard fuel. The equipment apparatus setup for blending process is depicts in Figure-5.

The purified crude oil methyl ester and diesel from separate tank were released by controlling the mass flow of fluids to attain preference ratio. The fluids will premixing before entering the main mixing chamber. During blending process, the scale blending machine will be operated under temperature around 70°C and the mixture will be stirred at 60°C for one hour. The mixture will be stirred continuously with rotating blender blade speed was set to maintain at 270 rpm.

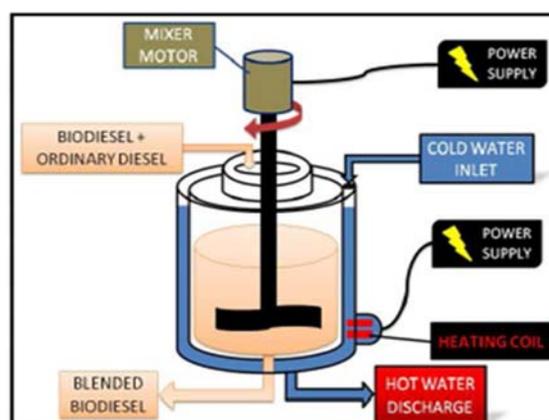


Figure-5. Illustration of equipment apparatus setup for blending process.

Table-1. Measured fuel properties of all the tested blends.

Fuel type	Density	Kinematic viscosity	Flash point	Water content	Acid value
Unit	(kg/m ³)	(mm ² /s)	(°C)	(mg/kg)	(mgKOH/g)
DSL	833.74	3.01	83	79.6	0.423
CPO5	837.05	3.01	91.5	120.1	0.259
JCO5	846.22	4.01	118	90.1	0.732
WCO5	836	3.01	89.9	90.4	0.124
Test method and specification limit based on adopted in MS Standard	ASTM D1298 (880 max) EN ISO 3675 (860 – 900)	ASTM D445 (1.9 – 6.0) MS 1831	ASTM D93 (43 min) MS 686	ASTM E203 (500 max) EN ISO 12937 (500 max)	ASTM D664 (0.8 max) MS 2011

Measurement of fuel properties

Next, the properties of biodiesel blends fuel has been analysed and recorded. In the study, the properties of biodiesel fuels were analysed precisely to comply the standard specification provides in Malaysia Standard (MS 2008:2008) and must be comparable to standard diesel properties because it will directly affecting the performance and emissions of diesel engines. The properties of biodiesel are depending very much on the nature of its raw material or feedstocks as well as the technology and process utilised for its production. The properties of DSL and all types of biodiesel fuel blends have been measured within ambient temperature to conform the MS Standard. Table-1 displays the standard requirement and summarizes the comparison of fuel properties characteristics that has been measured between the DSL and biodiesel at particular blending ratio.

The blended biodiesel fuels properties are tested to ensure meets the MS Standard. The kinematic viscosity of biodiesel was measured by Hydromatation Viscolite 700 model VL700-T15 viscometer. Kinematic viscosity denoted as resistance of liquid to flow. It is refer to the time taken by a volume of biodiesel sample (liquid form) to flow under gravity through a calibrated glass capillary viscometer. Based on Malaysian Standard the range of

kinematic viscosity is 1.9 – 6.0 mm²/s. The density of fuel was measured by Metter Toledo Diamond Scale model JB703-C/AF. Density is the connexion between the mass and volume of fuel and expressed in units of kilograms per metre cubic (kg/m³). The density of biodiesel adopts in Malaysian Standard is in the range of 860-900 g/cm³. The density of biodiesel gives an indication of the delay between the injection and combustion of the fuel (ignition quality) and the energy per unit mass (specific energy). The flash point of biodiesel were measured by using flash point analysis instrument namely Pensky-Martens model PMA 4. The flash point is the lowest temperature at which fuel emits enough vapours to ignite and is set to minimum range temperature of 43°C for petrodiesel and 101°C for biodiesel as adopt in Malaysian Standard. The water content and acid values in biodiesel sample measured by Volumetric KF Titrator model v20 and undergo titration process. The term of acid value is expressed as the amount in (milligram) of potassium hydroxide (KOH) required neutralizing 1 gram of the biodiesel and is set to a maximum value of 0.8 mg KOH/g as in the Malaysian Standard. Higher acid content can cause severe corrosion in fuel supply system and internal combustion engine. During acid value measurement, the biodiesel sample is titrated with alcoholic KOH using phenolphthalein as



indicator. The standards of water content for biodiesel in Malaysia Standard is set to a maximum 500 mg/kg or limit 0.05% maximum by volume.

Engine performance and gas emission experimental setup and procedure

Marine auxiliary engine also known as marine auxiliary machinery is a marine engine for other used which is not used to propel a water-borne vessel or ship prime mover. The marine auxiliary engine normally installed on-board medium size vessel or ship and known as auxiliary machinery. Marine engines in common used are 2-stroke diesel engines, steam turbines and gas turbines. Marine auxiliary engine as well as marine machinery must have to meet higher standards of reliability and greater demands for weight and volume reduction and access for maintenance. Marine machinery also must be capable of withstanding the marine environment, which tends toward extreme ambient conditions, high humidity, sea-water corrosion, vibration, sea motions, shock, variable demand and fluctuating support services.

Facilities and equipment in this study were set up in Multifuel Engine Laboratory in Department of Marine Engineering in Ungku Omar Polytechnic Malaysia. Fuels were tested using a marine auxiliary diesel engine, model TF120-ML with 0.638 litre capacity, single cylinder, horizontal type, 4-cycle engine with air-cooled system made by Yanmar Motor. The engine was designed with compact dimensions and in all applications with a power requirement up to 8.8 kW at 1 hour due to its low weight. Table-2 signified the specification of the test engine.

Table-2. Test engine specification.

Item	Specification
Engine Model	YANMAR TF120-ML
Type	1 cylinder, horizontal, air and water-cooled, 4 stroke
Combustion System	Direct injection
Aspiration	Natural aspiration
Cylinder Bore x Stroke	92 mm x 96 mm
Displacement	0.638 litre
Max. Output Power	12 Ps (8.8 kW) at 2400 rpm
Starting System	Manual and auto starting
Lubrication System	Complete enclosed forced lubricating system
Electrical System	Alternator, 12 V-45 W
Fuel Tank Capacity	11 litre
Engine Oil Capacity	2.8 litre

The main engine performance parameters or output parameters measured are temperature, torque and brake power. These parameters were measured by an Eddy current dynamometer system. The Eddy current dynamometer which works as load controller exerted to

the engine or engine brake is connected to the engine through a coupling shaft while a specific computer set was integrated and synchronised with the engine particularly the transducer at the engine dynamometer. The function of this transducer is to analyse and measure data from the dynopack and send to the encoder/data acquisition system (DAQ) before being converted/encoded for computer uses. The dashed line shows the link connection from main particular sensor attached with the engine dynopack to DAQ and connect to a Supervisory Control and Data Acquisition (SCADA) unit which is computerised and monitored. The test engine and other testing apparatus set up has been arranged as in Figure-6. The operating parameters such as loads exerted during engine operation and engine speeds will be controlled manually, set by user while the overall operation of the engine will be automatically monitored by SCADA unit through the computer. Additionally, the engine also installed with combustion analyser probes or pressure transducer which may be used to analyse the combustion characteristics as well as ignition behaviour. The DEWESOFT v7.11 software is used to monitor the input parameters and measure the performance of the engine while the DYNO-MAX 2010 software is used to analyse the combustion characteristics.

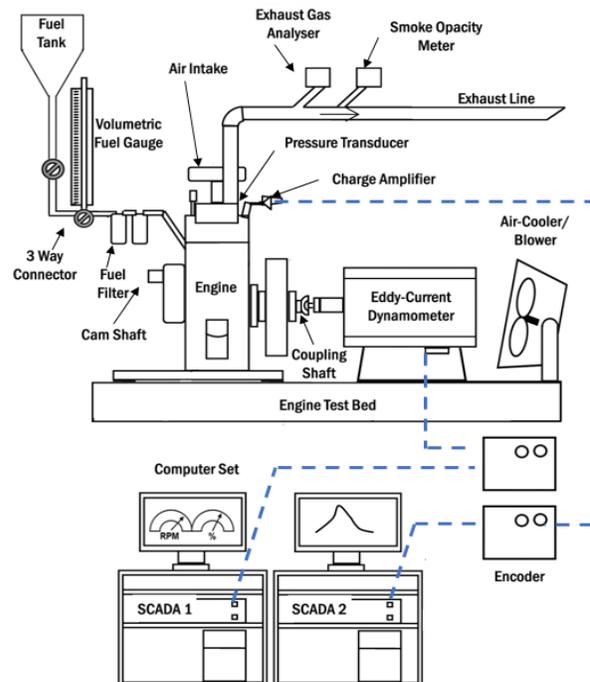


Figure-6. Schematic of experimental setup.

Separately, the exhaust gas emissions such as carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbon (HC) and oxides of nitrogen (NO_x) will be analysed and measured using an autocheck 5 channel exhaust gas analyser model IMR 2800-A as specified in Table-3. The sampling probes of gas analyser were



mounted at the centre of the exhaust pipe during measurement of the gas emissions.

Table-3. Exhaust gases analysis specifications.

Parameter	Resolution	Accuracy	Range
CO ₂ (Carbon dioxide)	0.01%	± 4 % rel.	0-10 %
CO (Carbon monoxide)	1 ppm	± 4 % rel.	0-3000 ppm
NO _x (Oxide of nitrogen)	1 ppm	± 4 % rel.	0-5000 ppm
HC (Hydrocarbon)	1 ppm	± 2 %	0-30000 ppm

For this research, the fuels tested of DSL, CPO, JCO and WCO5 are used for running in a manner of similar engine operation conditions. This means the total 4 different fuels in numbers has been tested. The engine was operated under dynamometer loads at 0%, 50% and 90% loads condition. Since the fuel test or engine operating hours taking a longer period of times, the maximum load i.e. 100% was not taken into account to prevent the engine and its component from exhausted, fatigued and risk of engine failure as well as engine safety precaution. Another parameter in the experiment is the various running speed of the engine which are simulated at 800 rpm (minimum speed), 1200 rpm, 1600 rpm and 2000 rpm (maximum speed).

The parameters measured with respect to engine performance consists of engine torque, brake power (BP), brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE), exhaust gas temperature (EGT) and fuel mass flow rate (\dot{m}_f). In conjunction, the measurements of exhaust gas emissions comprised of carbon dioxide (CO₂), carbon monoxide (CO), oxides of nitrogen (NO_x) and hydrocarbon (HC) using exhaust gas analyser.

THEORY OF DIESEL ENGINE PERFORMANCE CALCULATION

Testing of engine performance is often important in the improvement and development of engine and fuel technologies. There are several steps and factors must be considered and taken into account to perform the calculation of performance of an internal combustion engine. The most critical performance measurements are output torque and speed. Torque (τ) is measured by attaching a load cell (force transducer) to the dynamometer housing. The load cell strains slightly with applied load, and the strain is measured using strain gauges connected to a preamplifier that outputs a voltage proportional to the load. In accordance with Newton's first law, the measured torque on the dynamometer housing equals to the torque on the dynamometer shaft while speed (N) is measured with a pickup the spinning dynamometer. A steel wheel with a small slot at periphery of the wheel is placed on the shaft and an inductive pickup is placed close enough to the wheel such that it generates pulses as the

small slot pass by. This time-based pulse signal is analysed in order to measure the period between pulses and converted to frequency. Since the engine output is taken directly from the crankshaft, then the dynamometer shaft speed equals the engine speed. The derivations of theories are as follow (Challen & Baranescu, 1999; Horizon, 2014; Rakopoulos & Giakoumis, 2009):

Brake power (P_b) is described as the output power of engine measured by developing the power into a brake dynamometer on the output shaft. The engine brake power is determined from the product of engine speed and torque by using the equation:

$$P_b = \tau \times \omega \times 10^{-3} \quad (1)$$

where P_b is brake power in kW, τ is shaft torque in Nm and ω is shaft rotational speed in rad/sec.

While the shaft rotational speed or engine speed must be converted from RPM to rad/sec as follows:

$$\omega = \frac{2 \times \pi \times N}{60} \quad (2)$$

where ω is engine speed in rad/sec and N is engine speed in RPM or rev/minute.

Fuel consumption rate is the ratio of the number of kilometres travelled to the number of litres (*volumetric fuel consumption*) or kilograms (*specific fuel consumption*) of fuel burned. It is desirable to obtain a lower value of fuel consumption rate means that the engine used less fuel to produce the same amount of work. In the experiment, the volumetric fuel consumption (FC_v) is measured using a volumetric fuel gauge where the fuels consumption was measured by the time to consume 100ml fuels. The specific fuel consumption (SFC) was measured using the following equation:

$$SFC = \rho \times FC_v \times 10^{-3} \quad (3)$$

where SFC is specific fuel consumption in kg/h, ρ is fuel density in kg/m³ and FC_v is volumetric fuel consumption in litre/h.

Brake specific fuel consumption (BSFC) is defined as the ratio of mass fuel consumption to the brake power which a convenient way to compare engines of different sizes with regard to the fuel consumption. From the definition of SFC , the $BSFC$ can be written by the equation:

$$BSFC = \frac{\text{Specific fuel consumption}}{\text{Brake power}} \quad (4)$$

$$BSFC = \frac{SFC}{P_b} \quad (5)$$

where $BSFC$ is brake specific fuel consumption in kg/kW.h, SFC is specific fuel consumption in kg/h and P_b is brake power in kW.



Brake mean effective pressure (BMEP) is the average (mean) pressure which imposed on the pistons uniformly from the top to the bottom of each power stroke which would produce the brake power. *BMEP* is calculated from measured dynamometer torque. One additional factor, n_c is the number of revolutions per power stroke, which is 2 for four-stroke engines and 1 for two-stroke engines. The equation to calculate *BMEP* is given by:

$$BMEP = \frac{P_b \times n_c}{V_d \times \frac{N}{60}} \times 10^{-3} \quad (6)$$

Since the torque, τ is related to the angular speed, N and power produced by Equation. (1), the equation of *BMEP* in terms of torque can be written as:

$$BMEP = \frac{\tau \times 2 \times \pi \times n_c}{V_d \times 60} \times 10^{-3} \quad (7)$$

where *BMEP* is the brake mean effective pressure in kPA, P_b is brake power in kW, τ is shaft torque in Nm, n_c is the number of revolutions per power stroke, V_d is the displacement of the engine in m^3 and N is the engine speed in RPM.

Brake Thermal Efficiency (BTE) commonly denoted as η_{th} is defined as break power of a heat engine as a function of the thermal power input from the fuel. It is signify how well an engine converts heat from a fuel to mechanical energy. The calculation of *BTE* is by:

$$BTE = \frac{\text{Brake power}}{\text{Fuel power}} \quad (8)$$

While fuel power (FP) is the thermal power released by burning fuel inside the engine is calculate using equation:

$$FP = SFC \times CV \quad (9)$$

Hence, the *BTE* can be calculating using the equation as follows:

$$BTE = \frac{3600 \times P_b}{SFC \times CV} \quad (10)$$

where *BTE* is brake thermal efficiency which is dimensionless, FP is fuel power in kJ/h, P_b is brake power in kW, SFC is specific fuel consumption in kg/h and CV is calorific value of kilogram fuel in kJ/kg.

RESULTS AND DISCUSSIONS

All types of biodiesel blends that comprised of crude palm oil (CPO), jatropha curcas oil (JCO) and waste cooking oil (WCO) were analysed concurrently with comparing to the standard diesel (DSL) results of engine performance and exhaust gas emissions. The discussion

are encompassed the analysis of performance and emission characteristics through engine speed 800 rpm to 2000 rpm at an interval of 400 rpm under 0% (no load) and 50% (intermediate load) and 90% (maximum) dynamometer loads condition. The engine performance that measured are consists of torque, brake power (P_b), brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE) and exhaust gas temperature (EGT).

Analysis of engine performance

The changes in torque, brake power (P_b), brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE) and exhaust gas temperature (EGT) from diesel engine fuelled by biodiesel blends of CPO, JCO, WCO and standard diesel (DSL) with respect to the increment of engine speed from 800 rpm to 2000 rpm under load exerted of 0%, 50% and 90% are given by Figure-7, Figure-8 and Figure-9 respectively. Throughout the range of speeds, CPO and JCO were observed has produced a higher engine performance with declining trends in term of torque, brake power, BMEP and BTE as compared to that of DSL under 0% load condition except for WCO. In contrariwise, lower BSFC produced by CPO and JCO as compared to that of DSL was observed. Meanwhile, WCO was remarked has yielded higher BSFC as in Figure-7. The higher BSFC is caused by higher kinematic viscosity of biodiesel may cause poor atomisation of the fuel, hence poor mixing with air resulting in higher BSFC. EGT produced by all biofuels is increase proportional to engine speed. While the EGT is comparable to that of DSL around 1200 rpm to 1600 rpm but lower than DSL at highest engine speed.

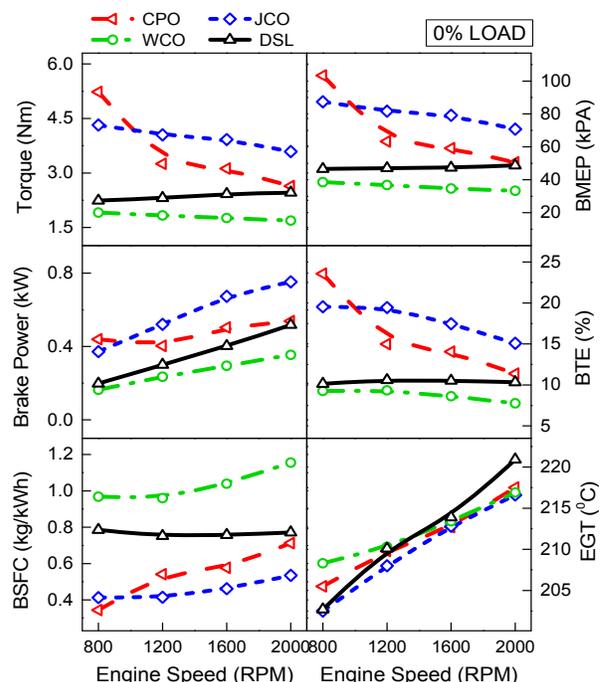


Figure-7. Engine performance characteristic by biodiesel throughout engine speed without load condition.



As the loads was increased to 50%, the highest engine performance obviously remarked by JCO particularly in torque, brake power, BMEP and BTE along with lowest BSFC as depicts in Figure-8. This is followed by the engine performance of CPO at the second place particularly in torque, brake power, BMEP, BTE and EGT associated with comparable measurement of torque, brake power and BMEP to DSL during 1600 rpm to 2000 rpm engine speed. However the BSFC of CPO is slightly lower than that of DSL. On the other hands, a decreased in engine performance by WCO was remarked under medium rated loads. In addition, the WCO fuel also produced higher BSFC and EGT than that of DSL under 50% load condition. However, the BTE produced by WCO is about similar to that of DSL under 50% load conditions throughout range of engine speed. In overall, it is clearly observed that the performance of diesel engine demonstrates an increasing trends corresponding to the increasing of engine speed for all fuels tested under 50% dynamometer load conditions. In addition, the higher EGT yielded by all biodiesels fuels than DSL under 50% exerted loads with maximum variants around 5°C indicates that higher combustion temperature has taken place inside the combustion chamber.

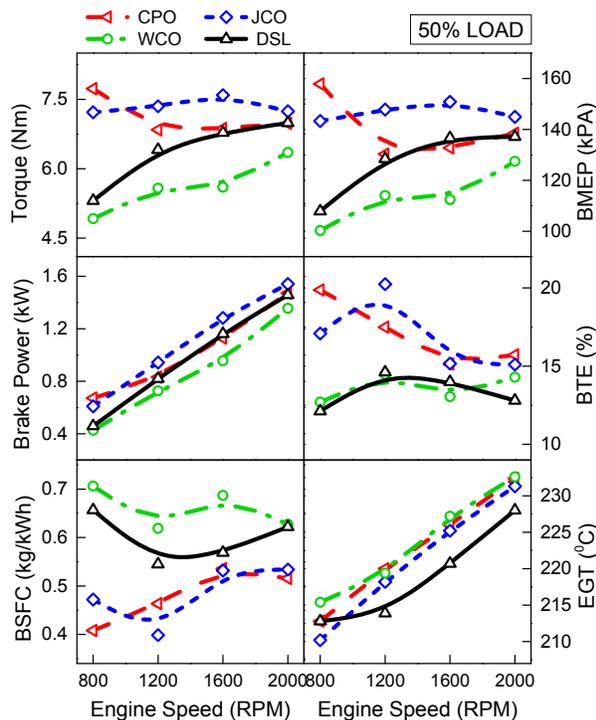


Figure-8. Engine performance characteristic by biodiesel throughout engine speed under 50% load condition.

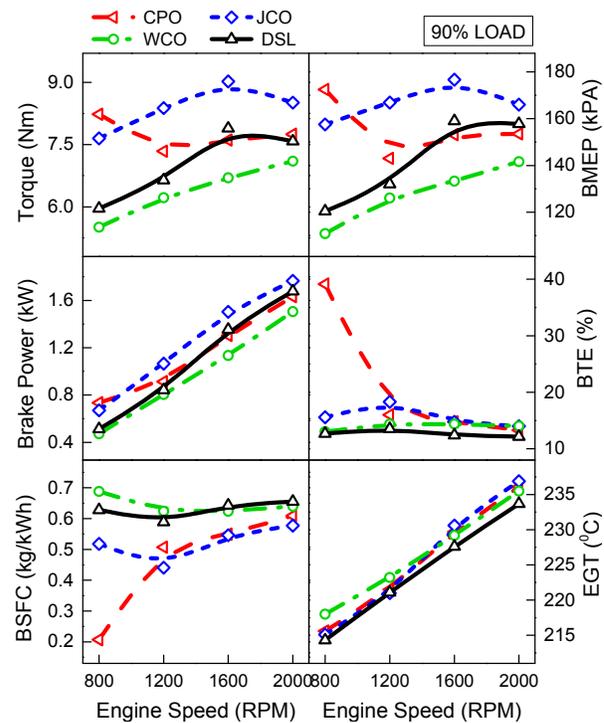


Figure-9. Engine performance characteristic by biodiesel throughout engine speed under 90% load condition.

Under maximum dynamometer brake loads, once again JCO is observed having the highest engine performance in term of torque, brake power BMEP and BTE among the all fuels tested as illustrates in Figure-9. In contradictory, the torque, brake power and BMEP of WCO are the lowest among all fuels tested. However, the brake power, BTE and BSFC of WCO are about comparable to that of DSL under 90% loads condition. Apart from that, an abnormality graph by CPO is denoted where the measurement of torque, BMEP and BTE is quite higher during lower speed of 800 rpm but then normal when the speed increased from 1200 rpm to maximum as shows in Figure-9. This abnormality or inconsistent behaviour might be happened during the beginning of the increasing of load from 50% to 90%. Aside, the EGT of all biofuels tested was increased proportional to increasing of engine speed and about comparable to DSL with small variants under maximum dynamometer loads exerted.

Analysis of exhaust gas emissions

The changes in formation of CO₂, CO, NO_x and HC emissions from diesel engine fuelled by CPO, JCO and WCO blends fuels corresponding to 5% blending concentration as well as neat diesel i.e. DSL throughout the range of engine speed under loads condition of 0%, 50% and 90% are demonstrates in Figure-10, Figure-11 and Figure-12 respectively. From the fuel testing, it was remarked that JCO produced higher CO₂, NO_x and HC gas emission as compared to that of DSL associated with comparative CO gas to DSL under 0% dynamometer load exerted as shown in Figure-10. The high NO_x gas



produced by JCO is mainly due to the fact that JCO blends fuel has high oxygen content that will attributed to better combustion and directly yielding the higher NO_x emission. However, the combustion of WCO fuel in diesel engine given about comparable exhaust emission to that of DSL particularly in CO₂, NO_x and HC gases. In the meantime, it was observed that the production of CO₂ gas by CPO is tolerable to DSL during lower engine speed of 800 rpm but the CO₂ emission was then significantly increased as the engine speed increased. In conjunction, a good sign of CO gas reduction by CPO was remarked when the gas was emitted lower than that of neat diesel except through maximum engine speed which slightly higher than that of DSL.

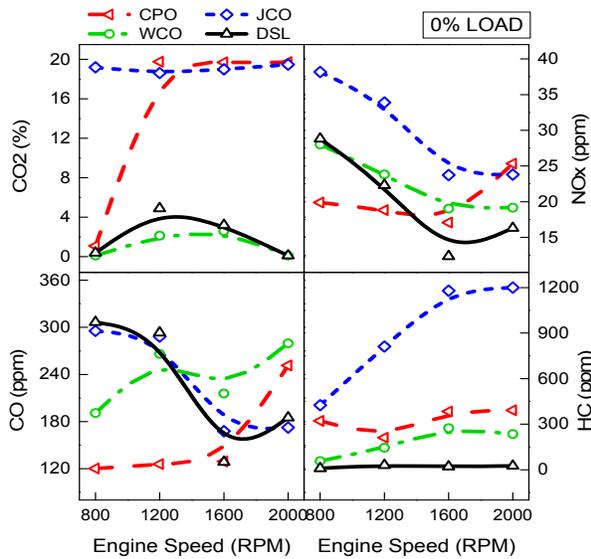


Figure-10. Exhaust gas emission characteristic by biodiesel throughout engine speed without load condition.

As the intermediate (50%) dynamometer loads were exerted, once again the JCO fuel resulting a higher emission of CO₂, NO_x and HC relative to that of DSL while a comparable CO gas emission was remarked as depicts in Figure-11. On the other hands, also observed from the graph that both CPO and WCO a slightly reductions of CO₂ emissions, a slightly increased of NO_x emissions and about comparative CO and HC emissions to that of DSL. In overall, the production of CO gas emissions for all fuels indicates about comparable results to DSL with reduction trends all over the range of speed.

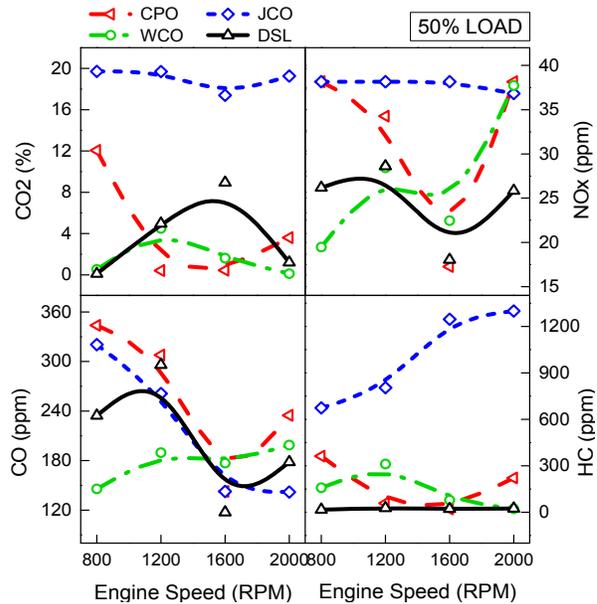


Figure-11. Exhaust gas emission characteristic by biodiesel throughout engine speed under 50% load condition.

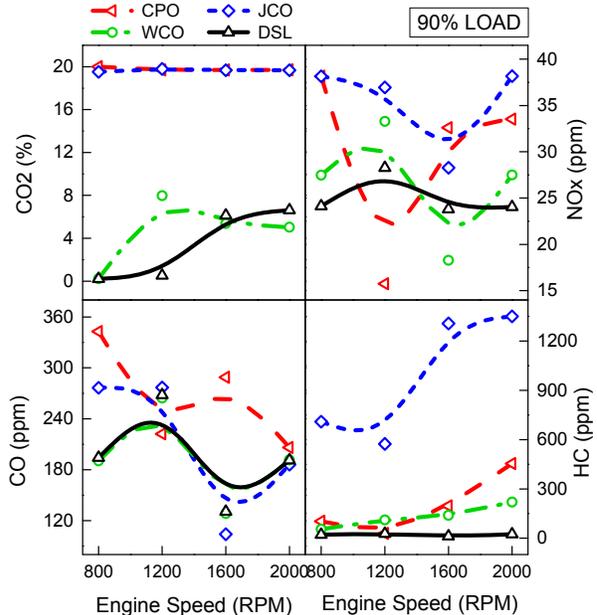


Figure-12. Exhaust gas emission characteristic by biodiesel throughout engine speed under 90% load condition.

Apart from that, by referring to Figure-12 a higher CO₂ emissions by CPO and JCO associated with comparative CO₂ emissions to that of DSL by WCO were observed as the dynamometer loading parameter increased to the highest load of 90%. An inconsistent NO_x gas emissions was remarked by all tested fuels with the highest signified by JCO under maximum rated loads. Aside, the combustions of JCO and WCO in diesel engine contributes somewhat comparable CO gas emissions to



DSL while CPO produced a slightly higher CO gas emission as compared to that of DSL. In other hand, the combustion of DSL yielding almost uniform HC emissions corresponding to the range of engine speed while the combustion of all biofuels signified the increment trends. The combustion of CPO and WCO contributes to a slightly increased of HC emissions comparative to that of DSL under 90% load conditions throughout engine speed. Nevertheless, JCO resulting the highest HC emissions among the tested fuels.

CONCLUSIONS

The study has been accomplished using three types of alternative biodiesel derived from CPO, JCO and WCO particularly in 5%vol blending ratio in order to investigate the engine performance and exhaust gas emissions characteristic for 0, 50 and 90% loads condition throughout 800, 1200, 1600 and 2000 rpm engine speeds. The conclusion based on the experimental study were lay emphasis on fuels characteristic that optimised the engine performance and exhaust emissions blends and are drawn as follows:

- CPO promotes a fair result on overall engine performance and a slight improvement in BTE as well as lower BSFC under all rated loads condition compared to that of DSL. In addition, CPO promotes about reasonable exhaust gas emissions compared to that of DSL for all types of gases examined.
- JCO promotes the greatest results among the biofuels tested where promotes clear enhancement on overall engine performance compared to that of DSL which comprises of torque, brake power, BMEP, BTE as well as better BSFC. In conjunction, JCO also promotes almost similar CO emissions to that of DSL except for rest of exhaust emissions which higher than that of DSL.
- WCO promotes a fair result in BTE, a slight decrease of brake power while reductions on the rest of engine performance associated with higher BSFC relative to that of DSL. Furthermore, WCO also promotes a better and slight reduction of CO₂ gas productions, about analogous CO and NO_x emissions with the exception of HC emissions which higher than that of petroleum diesel or DSL.

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NOMENCLATURE

η_{th}	Brake thermal efficiency
n_c	Additional factor: Number of revolutions per power stroke; 2 for 4-stroke engines and 1 for two-stroke engines
\dot{m}_f	Fuel mass flow rate
ρ	Fuel density
τ	Torque
ω	Shaft rotational speed
FC_v	Volumetric fuel consumption
N	Engine speed in rpm
P_b	Brake power
V_d	Displacement of engine
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrocarbon
KOH	Potassium hydroxide
NO_x	Oxides of Nitrogen
O_2	Oxygen

ABBREVIATIONS

<i>BMEP</i>	Brake mean effective pressure
<i>BP</i>	Brake power
<i>BSFC</i>	Brake specific fuel consumption
<i>BTE</i>	Brake thermal efficiency
<i>CPO</i>	Crude palm biodiesel oil
<i>CV</i>	Calorific value
<i>DAQ</i>	Data acquisition system
<i>DSL</i>	Standard diesel
<i>EGT</i>	Exhaust gas temperature
<i>FFA</i>	Free fatty acid
<i>FP</i>	Fuel power
<i>GHG</i>	Greenhouse gases
<i>JCO</i>	Jatropha curcas biodiesel oil
<i>ppm</i>	Part per million
<i>rel.</i>	Relative
<i>rpm</i>	Revolution per minute
<i>SCADA</i>	Supervisory Control and Data Acquisition
<i>SFC</i>	Specific fuel consumption
<i>WCO</i>	Waste cooking biodiesel oil

REFERENCES

- Abedin, M. J., Masjuki, H. H., Kalam, M. A., Sanjid, A., Rahman, S. M. A., & Fattah, I. M. R. 2014. Performance, emissions, and heat losses of palm and jatropha biodiesel blends in a diesel engine. *Industrial Crops and Products*, 59, 96-104.
- Adaileh, W. M., & Al-Qdah, K. S. 2012. Performance of Diesel Engine Fuelled by a Biodiesel Extracted From A Waste Cooking Oil. *Energy Procedia*, 18, 1317-1334.
- Anand, R., Kannan, G. R., Nagarajan, S., & Velmathi, S. 2010. Performance Emission and Combustion Characteristics of a Diesel Engine Fueled with Biodiesel



Produced from Waste Cooking Oil. SAE Technical Paper: 2010-01-0478.

ASTM American Society for Testing and Materials. 2012. ASTM Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels. West Conshohocken: ASTM D6751.

Atabani, A. E., Silitonga, A. S., Anjum, I., Mahlia, T. M. I., Masjuki, H. H., & Mekhilef, S. 2012. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Journal of Renewable and Sustainable Energy Reviews*, 16(4), 2070-2093.

Atabani, A. E., Silitonga, A. S., Ong, H. C., Mahlia, T. M. I., & Masjuki, H. H. 2013. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renewable and Sustainable Energy Reviews*. 18, 211-245.

Challen, B., & Baranescu, R. 1999. Diesel Engine Reference Book. 2nd ed., UK: Butterworth-Heinemann. 5-25.

Demirbas, A. 2008. Biodiesel: A Realistic Fuel Alternative for Diesel Engines. Trabzon Turkey: Springer-Verlag London Limited.

Department of Standards Malaysia. 2008. MS 2008:2008 Automotive fuels - Palm Methyl Esters (PME) for diesel engines - Requirements and test methods. ICS: 75.160.20.

Ejilal, I.R., Asere, A.A., Adisa, A. B., & Ejila, A. 2010. The effect of diesel fuel-Jatropha curcas oil methyl ester blend on the performance of a variable speed compression ignition engine. *Australian Journal of Agricultural Engineering (AJAE)*, 1(3), 80-85.

European Standard. 2008. Automotive fuels - Fatty acid methyl esters (FAME) for diesel engines - Requirements and test methods. Brussels: EN14214.

Horizon, G. 2014. Small Engine Dynamometer Testing, Performing Dynamometer Testing on Combustion Engines -Application Note. USA: Keysight Technologies. 1-15.

Hosseini, M., Ashnani, M., Johari, A., & Hashim, H. 2014. A source of renewable energy in Malaysia, why biodiesel? *Journal of Renewable and Sustainable Energy Reviews*. 35, 244-257.

Jindal, S. 2010. Effect of engine parameters on NOx emissions with Jatropha biodiesel as fuel. *International Journal of Energy and Environment*. 1(2), 343-350.

Khalid, A., Anuar, M. D., Ishak, Y., Manshoor, B., Sapit, A., Leman, M., & Zaman, I. 2014. Emissions Characteristics of Small Diesel Engine Fuelled by Waste Cooking Oil, in MATEC Web Conference, 13(06), 1-6.

Khalid, A., Anuar, M. D., Sapit, A., Razali, A., Manshoor, B., Fawzi, M., & Zaman, I. 2014. Experimental Investigation of Emissions Characteristics of Small Diesel Engine Fuelled by Blended Crude Palm Oil. *Applied Mechanics and Materials*. 660, 462-467.

Khalid, A., Mudin, A., Jaat, M., Mustaffa, N., Manshoor, B., Fawzi, M., ... Ngali, Z. 2014. Effects of Biodiesel Derived By Waste Cooking Oil on Fuel Consumption and Performance of Diesel Engine. *Applied Mechanics and Materials*. 554, 520-525.

Khalid, A., Nursal, R. S., Tajuddin, A. S. A. & Hadi, S. A. 2016. Performance and Emissions Characteristics of Alternative Biodiesel Fuel on Small Diesel Engine. *Journal of Engineering and Applied Sciences*. 11(12), 7424-7430.

Khalid, A., Osman, S. A., Jaat, N. M., Mustaffa, N., Basharie, S. M., & Manshoor, B. 2013. Performance and Emissions Characteristics of Diesel Engine Fuelled by Biodiesel Derived from Palm Oil. *Applied Mechanics and Materials*. 315, 517-522.

Kinoshita, E., Myo, T., & Hamasaki, K. 2006. Diesel Combustion Characteristics of Coconut Oil and Palm Oil Biodiesels. SAE Technical Paper: 2006-01-325.

Koh, M. Y., Idaty, T., & Ghazi, M. 2011. A review of biodiesel production from *Jatropha curcas* L. oil. *Renewable and Sustainable Energy Reviews*. 15(5): 2240-2251.

Liaquat, A. M., Masjuki, H. H., Kalam, M. A., Varman, M., & Hazrat, M. A. 2012. Experimental Analysis on Engine Performance and Emission Characteristics Using Biodiesel Obtained from Non-Edible Oil, in Regional Conference on Automotive Research, 6(3), 659-665.

Lim, S., & Teong, L. K. 2010. Recent trends, opportunities and challenges of biodiesel in Malaysia: An overview. *Renewable and Sustainable Energy Reviews*. 14, 938-954. Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., & Norhasyima, R. S. 2011. Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review. *Renewable and Sustainable Energy Reviews*. 15(8), 3501-3515.

Ong, H.C., Mahlia, T.M.I., Masjuki, H.H., & Norhasyima, R.S. 2011. Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review. *Renewable and Sustainable Energy Rev*. 15, 3501-3515.

Payri, F., Macián, V., Arrègle, J., Tormos, B., & Martínez, J. 2005. Heavy-Duty Diesel Engine Performance and Emission Measurements for Biodiesel (from Cooking Oil) Blends Used in the ECOBUS Project. SAE Technical Paper: 2005-01-2205.



Rakopoulos, C. D., & Giakoumis, E. G. 2009. Diesel Engine Transient Operation: Principles of Operation and Simulation Analysis. Athens, Greece: Springer-Verlag London Limited. 115-140.

Rosca, R., Rakosi, E., & Manolache, G. 2005. Fuel and Injection Characteristics for a Biodiesel Type Fuel from Waste Cooking Oil. SAE Tech. Paper, 724: 2005-01-3674.

Sani, W., & Hasnan, K. 2008. UTHM Biodiesel Pilot Plant Development, in Proceedings of International Conference on Mechanical & Manufacturing Engineering (ICME2008). 59(2), 1-8.

Sani, W., Hasnan, K., Md Yusof, M. Z., & Baba, I. 2013. Multi stage Transesterifications of High FFA Feedstock towards a High Conversion of Biodiesel in A Batch Mode Production Plant. Intern. Journal of Mining, Metallurgy & Mechanical Engineering (IJMMME), 1(5), 280-285.

Selvam, D., Panneer, J., & Vadivel, K. 2012. Performance and Emission Analysis of DI Diesel Engine Fuelled with Methyl Esters of Beef Tallow and Diesel Blends. Procedia Engineering, 38, 342-358.

Vasudevan, P. T., & Briggs, M. 2008. Biodiesel production: Current state of the art and challenges. Journal of Industrial Microbiology & Biotechnology. 35(5), 421-30.

Yoshimoto, Y., Onodera, M., & Tamaki, H. 1999. Reduction of NO_x, Smoke, and BSFC in a Diesel Engine Fueled by Biodiesel Emulsion with Used Frying Oil. SAE Technical Paper. 724: 1999-01-3598.