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Biodiesel production, properties and emissions test characteristics of non-edible fuels in Diesel engine

A. M. Ruhul *, H. H. Masjuki, M. A. Kalam, S. A. Shahir, S. S. Reham, I. Shancita

Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Abstract: In this study, two potential non-edible biodiesel feed stocks "*Croton megalocarpus*" and "*Ceiba pentandra*" have been used for esterification and Trans esterification process. Biodiesel characterization, engine performance and emission characteristics were investigated in an unmodified direct injection, naturally aspirated, single cylinder diesel engine. 20% (v/v) of each *C. megalocarpus* (CM), *C. pentandra* (CP) and their combined blends (CM20, CP20, CM15CP5, CM10CP10, and CM5CP15) were tested under varying engine speed ranging from 1400 rpm to 2400 rpm at full load condition. CM20 and CP20 reduced the brake power (BP) by 9.74% and 5.68%, brake thermal efficiency (BTE) by 3.71% and 1.31%, carbon monoxide (CO) emission by 2.55% and 3.80%, respectively compared to petroleum diesel. On the other hand, CM20 and CP20 increased the brake specific fuel consumption (BSFC) by 3.71% and 1.31%, NO_X emission by 10.75% and 12.37%, respectively. A mixture of 10% of both biodiesels with diesel (CM10CP10) provides better performance and emission characteristics. CM10CP10 reduced BP, BTE and CO by 0.53%, 0.47% and 6.48%, respectively and increased BSFC and NO_X by 1.87% and 15.25% respectively compared to ordinary diesel.

Key words: Performance; Emission; Croton oil; Ceiba oil; Esterification; Tran's esterification

1. Introduction

The quick consumption and rising costs of petroleum fuel other than their harmful emission are the primary concerns to look for alternative renewable sources (Reyes-Trejo et al., 2014). Biodiesel is the most convenient alternative source that could play a very important role to meet the energy demand, especially in automobile and power generation sector. Generally, it is synthesized from edible oils due to abundance and low free fatty acid content. On the other hand, the consideration is essentially engaged towards biodiesel from non-edible feedstocks as dependency on edible source poses a threat to food supply. In addition, production of biodiesel from non-edible feedstocks decreases the expense of biodiesel as these are fundamentally less expensive (Atabani et al., 2013). *Croton megalocarpus* (CM) and *Ceiba pentandra* (CP) are two of the potential non-edible feedstocks which have recently drawn the attention of the researchers (Kafuku et al., 2010; Khan et al., 2015; Ong et al., 2013).

Earlier studies have addressed the suitability of the biodiesel and its blends derived from these feedstocks in diesel engines. However, a combined blend of multiple feedstocks is being tested nowadays.

This experimental study examines the potential of using a combined blend of CP and CM biodiesel as a partial replacement for diesel fuel in a single-cylinder diesel engine. These biodiesels were blended based on the difference of cetane number (CN) between these two as the higher the CN, the better the combustion properties. ASTM D7467 suggests the blending of biodiesel with diesel from 6% to 20% (B6–B20). Biodiesel blends of up to 20% with diesel (B20) can be easily used in the existing diesel engines without the need for engine modification (Kalam et al., 2011). This study has particular relevance to South East Asian region where the potential exists for the availability of both of these feedstocks and the establishment of economically viable application of biodiesels from these oils.

2. Materials and methodology

The crude of *C. pentandra* oil, *C. megalocarpus* oil and other highly pure analytical grade chemicals, which are associated with biodiesel production, were purchased from local markets. The biodiesel production was carried out with 2100ml capacity a double jacketed batch glass reactor.

2.1. Biodiesel production

As the crude CM and CP oil both contains the high acid value (>4 mgKOH/g), acid esterification of those oils is recommended by researchers before going through trans esterification for lowering the acid value (Rizwanul Fattah et al., 2014). In this study 1000 ml, crude oil from both types was taken and preheats the oil at two different batch glass reactors at 60°C to produced biodiesel. Methanol (CH_3OH) to oil molar ratio 12:1 (50% v/v oil) was taken for CM

* Corresponding Author.

and 18:1 (75% v/v oil) for CP, 1% (v/v oil) of sulfuric acid (H_2SO_4) was added and maintained 60°C reaction temperature for 3 h with 900 rpm stirring speed. After that, products are poured into a separation funnel for 4h to separate excess CH_3OH, H_2SO_4 and other impurities. Esterified lower layer products were collected and preheated at 60°C for trans esterification.

Table 1: Psychochemical property of feedstocks, biodiesels and diesel-biodiesel blends

Property	Crude CM Oil	Crude CP Oil	CM100	CM20	CM15CP5	CM10CP10	CM5CP15	CP20	CP100
Density@40°C, kg/m^3	938.5	912.3	869.9	838.8	838.5	838.2	838.0	837.8	865.1
Kinematic viscosity @40°C, mm^2/s	44.5	33.5	4.1287	3.9182	3.9297	3.9386	3.9515	3.9625	4.2927
Dynamic viscosity @40°C, mPa.S	n.d.	n.d.	3.5917	3.2864	3.2949	3.3215	3.3115	3.3198	3.7137
Acid value, mgKOH/g	4.9	17.3	0.334	0.281	0.269	0.270	0.257	0.333	0.447
Flash point, °C	203	171	190	88	85	83	84	86	157
Calorific value, MJ/kg	n.d.	n.d.	39.95	44.39	42.66	42.09	42.28	43.87	39.79
Oxidation stability 110 °C, h	n.d.	n.d.	2.65	4.16	3.68	2.87	2.46	2.24	2.15
*Cetane number	n.d.	n.d.	42.4	n.d.	n.d.	n.d.	n.d.	n.d.	50.36
*Carbon, wt.%	n.d.	n.d.	76.88	n.d.	n.d.	n.d.	n.d.	n.d.	76.45
*Hydrogen, wt.%	n.d.	n.d.	12.08	n.d.	n.d.	n.d.	n.d.	n.d.	12.40
*Oxygen, wt.%	n.d.	n.d.	11.04	n.d.	n.d.	n.d.	n.d.	n.d.	11.14

n.d.= not determined, *Calculated value

In trans esterification process, 6:1 (25% v/v oil) methanol to oil molar ratio, 1% (w/w oil) of potassium hydroxide (KOH) were added and 60°C reaction temperature, 900rpm stirring speed was maintained for 2h in different batch glass reactor for both esterified products. After finishing the reaction, the products were poured again into a separation funnel for 12h to separate glycerol from biodiesels.

After draining the lower layer, upper biodiesel layer was washed with 60°C warm distilled water. The washing process was performed several times to properly remove the impurities. Then the produced biodiesel was undergoes to the mechanical and chemical drying process. A rotary evaporator (IKA RV-10) was used to evaporate methanol and water content from the biodiesel. For chemical drying, sodium sulfate anhydrous (Na_2SO_4) powder was used. Finally, filtration was performed to obtained desire clean and pure methyl ester. 96.5% yield and 97% yield was observed for CM and CP, respectively.

2.2. Characterization

The physicochemical property of crude CM oil, CP oil, produced biodiesel (CM100 and CP100) and different diesel-biodiesel blends (CM20, CM15CP5, CM10CP10, CM5CP15, CP20) were determined in the laboratory under several experiments. The measured results are represented in Table 1.

Fatty acid composition of the biodiesel sample was measured with the help of a GC (gas chromatographer). Agilent 7890 series, USA GC machine was used to measure the weight percentage of each FAME. It was observed that CPME contains the 28.1% saturated, 23.4% mono-unsaturated, and 48.6 % poly-unsaturated methyl ester. Among them, methyl oleate (C18:1) contains 22.6% and methyl lioleate (C18:2) contains 40.7%. On the other hand, CMME contains 11.7% saturated, 13.2% mono-unsaturated and 75.1% poly-unsaturated methyl ester. Among them, majority portion (about 71.2%) was possessed by methyl linoleate (C18:2). It was observed that about 16.3% higher unsaturated FAME contains in CMB than CPB. CN were calculated from the percentage of fatty acid content, Iodine Value (IV), Saponification Number (SN) and using the Eq. 1, Eq. 2 and Eq. 3, respectively (Krisnangkura, 1986).

$$SN=\sum ((560\times A_i)/ (MW_i)) \quad (1)$$

$$IV=\sum ((254\times D\times A_i)/ (MW_i)) \quad (2)$$

$$CN=(46.3+(5458/SN)-(0.225\times IV)) \quad (3)$$

3. Engine testing

To carry out the experiment a single cylinder, four strokes, naturally aspirated, direct injection engine was used. The engine test bed layout was presented in Fig. 1 and engines other technical data presented at Table 2. An eddy current dynamometer was coupled with the engine for applying the torque on the engine. Dynomax 2000 software with PC interface and a control unit was intergraded to test bed. A digital fuel flow meter was connected with the fuel flow line. BOSCH gas analyzer was used to measure the engine emission, especially smoke opacity. AVL DiCom 4000 the other emitted gases such carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_X), and hydrocarbon (HC).

4. Result and discussion

This study represents the impact of 20% different biodiesel blends (CM20, CM15CP5, CM10CP10, CM5CP15, and CP20) of CM and CP in direct injection diesel engine at full throttle (100% load) condition with different engine speeds ranging from 1400rpm to 2400rpm.

The engine performance mostly depends on fuel quality and fuel injection system (Habibullah et al., 2015). Basically, these fuel property hampers spray formation during fuel injection as well as it affects the combustion. Fig. 2 demonstrates that, for both diesel and biodiesel-diesel blend BP increases with the increasing of the engine speed, excluding 2400 rpm.

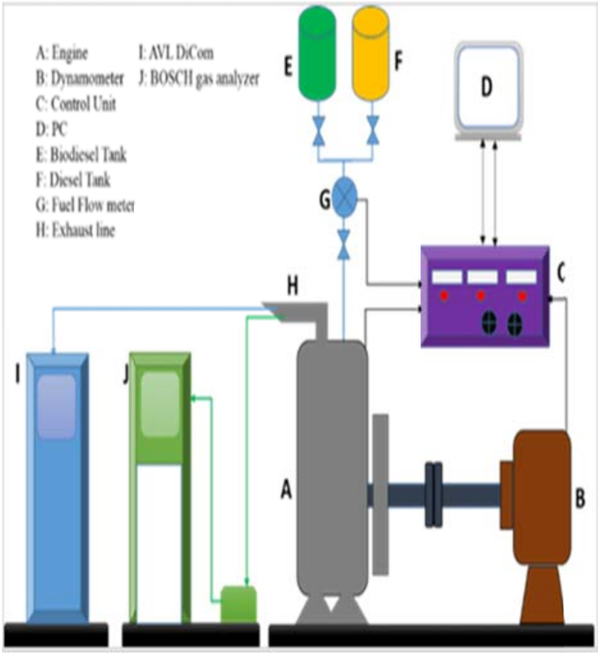

Fig. 1: Engine test bed setup

Table 2: Engine specification

Engine Details	
Engine type	: 4 Stroke DI diesel
Cylinder bore × stroke (mm)	: 92×96
Displacement (L)	: 0.638
Compression ratio	: 17.7
Maximum engine speed	: 2400 (rpm)
Maximum power (kW)	: 7.7
Injection timing (deg.)	: 17° before TDC
Injection pressure (kg/cm²)	: 200
Power take off position	: Flywheel side
Cooling system	: Radiator cooling
Connecting rod length (mm)	: 149.5
Fuel System	: Pump line nozzle injection

This exception could be ascribed to less time taken for fuel atomization (Rizwanul Fattah et al., 2014) and an increase of piston cylinder frictional forces with speed (Kalam et al., 2011). The maximum BP was recorded 7.60, 7.42, 7.45, 7.54, 7.59 and 7.55 kW for diesel, CM20, CP20 CM15CP5, CM10CP10, and CM5CP15, respectively at 2200 rpm. BP output level was lower (about 1% to 6%) for biodiesel blends than petrodiesel in all speeds. This can be attributed to high amount fuel injection, poor atomization, incomplete combustion and higher fuel-air ratio injected into the combustion chamber. All these happens because of higher viscosity, density and lower volatility (higher flash point compared to diesel) than petrodiesel (How et al., 2013). Besides, 13.12% lower calorific.

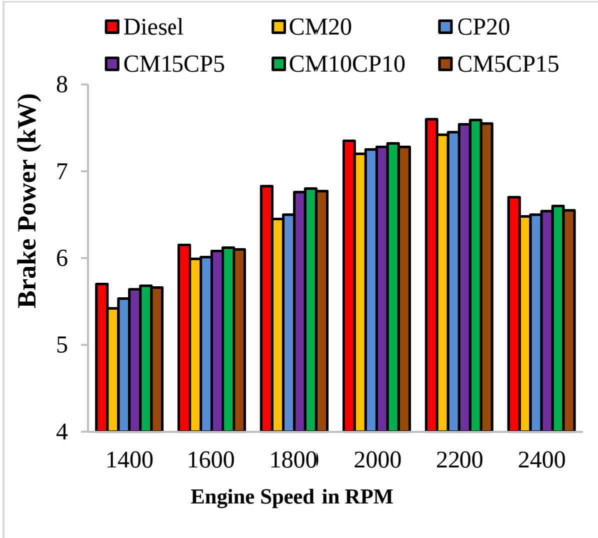

Fig. 2: Brake power with engine speed variation

Value of biodiesel can be attributed to the lower BP output than diesel. Among all the 20% biodiesel blends CM10CP10 showed the higher BP output at higher engine speed. This outcome can be attributed to the fact that low calorific value and high viscosity diminish the inner spillage in the pump (Buyukkaya et al., 2013; Can, 2014).

Fuel property particularly density, viscosity and calorific value have significant influences on engine BSFC (Arbab et al., 2014). Fig. 3 illustrates BSFC of biodiesel blends have higher consumption than petrodiesel due to the higher density and viscosity of biodiesel with compared to diesel. It also demonstrates that initially the BSFC for all fuels gradually decreasing with increasing engine speed till 1800 rpm. This can be ascribed as the increasing of the fuel atomization ratio, subsequently, the air-fuel equivalence ratio, which influences air and fuel mixing (Habibullah et al., 2015). The lowest BSFC for diesel, CM20, CP20, CM15CP5, CM10CP10 and CM5CP15 were recorded 250.16, 278.23, 271.14, 264.05, 255.21 and 258.06 g/kWh respectively, at 1800 rpm. After 1800rpm, BSFC gradually increased with the engine speed reached up to maximum 2400 rpm. This can be described as the volumetric efficiency decreases, with increasing the temperature as well as the engine speed which arises because of piston-cylinder frictional force. In addition, BSFC increases with increasing the load and biodiesel-diesel higher blend ratio as well as density and viscosity (Rizwanul Fattah et al., 2014). With increasing the amount of CPB blending ratio, BSFC decreased alone with density but increased viscosity. Among all the individual blends and combined blends CM20 showed the higher BSFC at 2400 rpm, because of the higher density and CM10CP10 showed the lowest BSFC at 1800 rpm.

Fig. 3 demonstrated that BTE improved until 1800 rpm, minimized along with engine speed, and achieved the lowest value at 2400 rpm for each of the investigated fuels. This outcome is usually attributed for the highest BSFC was attained due to the consolidated impact of poor fuel atomization time and elevated piston-cylinder frictional force at this speed (Imtenan et al., 2014).

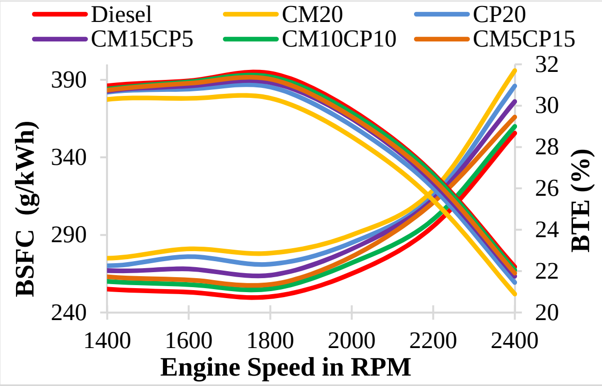

Fig. 3: BSFC and BTE with engine speed variation

The height BTE value for diesel, CM20, CP20, CM15CP5, CM10CP10 and CM5CP15 were recorded 31.57%, 30.36%, 30.90%, 31.12%, 31.40% and 31.28% respectively, at 1800 rpm. Compared to diesel maximum BTE of the biodiesel-diesel blend was decreased by 0.5% to 3.8%. BTE changed with the variety in BSFC and calorific value of the biodiesel fuel; though individual CM20 possess higher calorific value that CP20 but opposite for viscosity and CN. On the other hand, combined blending provides better density, viscosity as well as better CN rather than individual CM and CP blends. The addition of higher ratio of CP with CM increases BTE and thus, 10% combined blend of CM and CP provides the higher BTE as well as the lower BSFC among the biodiesel-biodiesel blends. A quick injection of biodiesel together with high CN results in the early start of combustion (SOC) (Imtenan et al., 2015). Early SOC raises pumping function and endorses heat decrease in the cycle (Can, 2014; Payri et al., 2015). This trend, collectively along with low heating value and higher density, viscosity, negatively impacts engine performance (Devan & Mahalakshmi, 2009; Park et al., 2012).

NO_X emission mainly includes nitric oxide (NO) and nitrogen dioxide (NO_2) emission to the environment. During combustion, atmospheric nitrogen (about 78.09% by volume) come into the. Atmospheric tripled bonded nitrogen behaves as an inert gas but in high combustion temperature it splits up and undergoes a series of reaction with oxygen and creates NO_2. This NO_X formation mechanism is known as Zeldovich mechanism. NO_X forms in prompt (Fenimore) mechanism because of the generation of hydrocarbon radicals via molecular unsaturation (Reham et al., 2015). In Fig. 4 NO_X was gradually increasing with engine speed as the combustion temperature increase. The height NO_X emission for diesel, CM20, CP20, CM15CP5, CM10CP10 and CM5CP15 were recorded 795.31, 845.10, 849.60, 837.90, 860.90 and 854.60 ppm, respectively at 2400 rpm. NO_X formation by the biodiesel blend is quite high due to 12-13 % higher oxygen content in biodiesel, which provides a high in-cylinder temperature for both premixed and diffusion combustion condition rather than diesel (Imtenan et al., 2015). Together with higher CN, air surplus.

co-efficient, residence time and higher bulk modulus of elasticity can be ascribed as the reason for NO_X formation (Imtenan et al., 2014). The bulk modulus of electricity causes the early nozzle opening and advancement of the ignition, which increase global fuel-air equivalence (Boehman et al., 2004). Because of the higher in-cylinder temperature during combustion, CM10CP10 gives slightly higher and CM15CP5 provides relatively lower NO_X emission among the tested biodiesel blends.

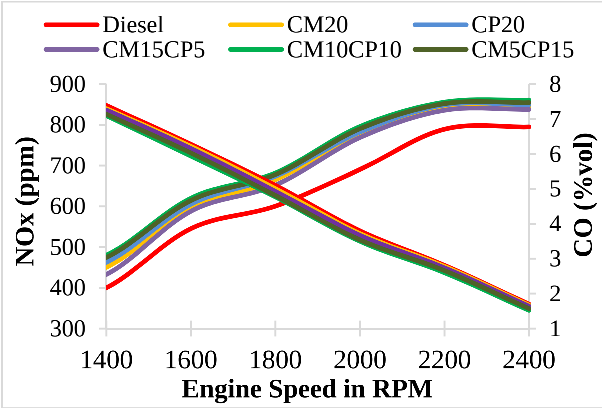

Fig. 4: NO_X and CO emission with engine speed

CO content in exhaust emissions is really the cause of partial combustion which caused by insufficient oxygen (Reham et al., 2015) supply during combustion. All this happens because of air-fuel ratio, fuel pressure, fuel type and injection timing. Among them ignition mixture because of lower air-fuel proportion can be considered as the main cause of CO emissions. Fig. 4 illustrates CO emission for all fuels decreases with increasing the engine speed. At lower speed higher fuel-air ratio was introduced during combustion, thus creates imperfect combustion. In addition higher cylinder temperature, higher pressure at higher speed reduces the CO emission (Can, 2014; Sayin, 2010) with the increases of engine speed. Overall biodiesel and biodiesel-diesel blends provide relatively lower CO emission in every speed. This can be ascribed as higher oxygen content and higher CN of biodiesel, thus shorting the ignition delay, which ensure better combustion and provides prevents less over-lean zones (Kalam et al., 2011). Maximum CO emission for diesel, CM20, CP20, CM15CP5, CM10CP10 and CM5CP15 were recorded as 7.39, 7.30, 7.18, 7.26, 7.10 and 7.14 % vol. respectively, at 1400 rpm. CO emission reduction for the biodiesel was obtained 1% to 11% with compare to diesel. Addition of CP in CM leads to an increase in viscosity and CN, decrease in density. Because of these combined effect among the biodiesel blends CM10CP10 provides lower CO emission.

5. Conclusions

In this study biodiesel was produced from two non-edible feedstocks and their physiochemical properties were examined. In addition, performance and emission characteristics of 20% biodiesel-diesel blend of CM & CP together with their combined blend were considered. These biodiesels were blended based on the difference of CN between these two as higher the CN, better the combustion properties. The average engine brake power for CM20, CP20, CM15CP5, CM10CP10 and CM5CP15 were lower (0.53%-3.70%) and BSFC were higher (1.87%-9.74) than that of diesel mainly owing to their lower HHV and higher density and viscosity. The BTE were slightly (0.47%-3.71%) lower than that of diesel fuel. The average NO_X emission were 8.37%-13.76% higher for all the tested biodiesel blends compared to diesel due to higher combustion temperature and presence of fuel-borne oxygen. The CO emissions were reduced to an extent of 1.35-6.48 compared to diesel burning. In conclusion, the lower brake power output and higher NO_X emission from burning of CM biodiesel blends can be improved by the addition of CP biodiesel.

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