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Fuel Properties of *Croton megalocarpus*, *Calophyllum inophyllum*, and *Cocos nucifera* (coconut) Methyl Esters and their Performance in a Multicylinder Diesel Engine

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Biodiesel has been considered recently as a viable alternative to fossil diesel fuels. This study aims to evaluate the potential of biodiesel production from *Croton megalocarpus* oil and compared it with coconut (*Cocos nucifera*) and *Calophyllum inophyllum* methyl esters. The study presents the physical and chemical properties of *Croton megalocarpus*, *Calophyllum inophyllum* and coconut methyl esters (CMME, CIME, and COME) together with their 10 and 20% blends by volume (B_{10} and B_{20}). This is followed by evaluating their blends in a multicylinder Mitsubishi Pajero diesel engine. It has been found that the properties of all biodiesel and their blends are comparable with ASTM D6751 and ASTM D7467 standards, respectively. Over the entire range of speed, it was found that the B_{10} and B_{20} blends of CMME, CIME, and COME result in average reduction in torque and brake power (BP) along with increased brake-specific fuel consumption (BSFC) compared to pure diesel fuel. With respect to engine emissions, the fuel blends resulted in an average reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions. However, the CMME and COME blends resulted in increased emissions of nitrogen oxides (NO) whereas CIME emits lower NO compared to pure diesel. It is concluded that B_{10} and B_{20} biodiesel blends can be used as diesel fuel substitutes without additional modifications.

Introduction

It appears inevitable that the escalating global energy demand along with climate change due to burning of fossil-fuel-derived energy sources has generated interest among researchers to develop alternative, sustainable, and clean renewable sources for fuels. As a renewable-energy source, biodiesel has caught the attention to be considered as a viable candidate due to its lower greenhouse-gas emissions along with the potential to reduce the dependency on imported fossil fuels and meet the global energy demand.[1–3] Biodiesel is an alternative fuel to diesel fuel that is produced by performing the transesterification of straight edible and nonedible vegetable oils, animal fats, tallow, waste cooking oil, and waste restaurant greases in the presence of catalyst. It has been reported that biodiesel possesses some important benefits such as being nonexplosive, biodegradable, nonflammable, renewable, and nontoxic, along with having inherent lubricity and a relatively high flash point; moreover it has similar properties with diesel fuel. Biodiesel can be blended with diesel fuel in small proportions (B_{10} and B_{20}) that can be used in compression-ignition (CI) engines without modification; these blends do not contain any harmful substances and produce less harmful emissions to the environment than diesel fuel.[4–7] There are 350 oil-bearing crops that have been recognized universally as prospective biodiesel feedstocks. These feedstocks are classified as either edible or nonedible. Palm oil, rapeseed oil, soybean oil, sunflower oil, coconut oil, and peanut oil are the most common biodiesel sources from edible oils whereas feedstocks such as *Croton megalocarpus*, *Calophyllum inophyllum*, *Jatropha curcas*, *Azadirachta indica* (neem), cotton, jojoba, rubber, *Moringa oleifera*, Mahua, castor, and animal tallow are the most common feedstocks from nonedible oils.[8–11] The advancement in such feedstocks will lead to the establishment of waste-to-wealth biodiesel production.

C. megalocarpus is a member of the *Euphorbiaceae* family. The tree can be found in natural forests, forest margins or as a canopy tree. *C. megalocarpus* is indigenous to East Africa (Burundi, Democratic Republic of Congo, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda). The tree grows to 15 to 35 m in height under the conditions of altitudes between 1300 and 2200 m with an annual rainfall between 800 and 1600 mm and average annual temperature varying between 11 and 26 °C. The fruit of *C. megalocarpus* contains

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3 ellipsoid-ovoid or oblong-ellipsoid seeds, 2.2–2.4 cm long and 1.2–1.4 cm wide. The tree produces up to 50 kg of seeds and a hectare produces 5–10 t of seeds per year. The seeds have an average oil content of 40–45 %.[12,13]

C. inophyllum is a member of the *Clusiaceae* family (commonly known as mangosteen family). The tree is also known as Polanga or Nagchampa in India, Nyamplung in Indonesia, or honne in the Philippines. It is a medium-sized, evergreen, submaritime tree that grows best in deep soil or on exposed sea sands. The annual rainfall requirement of the tree ranges between 750 and 5000 mm. The tree can be found growing in East Africa, India, Southeast Asia, Australia, and the South Pacific. The seed has very high oil content (65–75 %). *C. inophyllum* oil is nonedible and dark green.[12]

The *C. nucifera* tree is native to Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. However, it has an exotic distribution in many countries such as Argentina, Cameroon, China, Fiji, Madagascar, the United States, and Zanzibar. The trees have a smooth, columnar, light-grey/brown trunk, with a mean diameter of 30–40 cm at breast height, and they are topped with a terminal crown of leaves. The biophysical limits of the tree are as follows: altitude: 520–900 m, mean annual temperature: 20–28 °C, and mean annual rainfall: 1000–1500 mm. The fruits are green, at first, and turn brownish as they mature; yellow varieties go from yellow to brown.[10]

Objectives of the Study

The main objective of this paper is to study the potential of biodiesel production from crude *C. megalocarpus* oil as a promising nonedible biodiesel feedstock that can be obtained in different parts of the world and to compare it with the edible and nonedible oil sources from coconut (*C. nucifera*) and *C. inophyllum*, methyl esters (biodiesel), respectively.

Firstly, the study presents the physical and chemical properties of coconut, *C. inophyllum,* and *C. megalocarpus* methyl esters, together with their 10 and 20 % (*v*/*v*) blends, such as the kinematic viscosity, density, flash point, cloud point, pour point, cold-filter plugging point, viscosity index, and oxidation stability. This is followed by evaluating the 10 and 20 % blends in a multicylinder Mitsubishi Pajero diesel engine. It is evident that this study conducts a fully technical comparison between the edible feedstocks such as coconut and nonedible feedstocks such as *C. inophyllum* and *C. megalocarpus*, which is quite an important topic to many researchers and scholars in this research area.

Literature Review

In the last two decades, many studies have been performed regarding the potential of biodiesel production from edible-oil and nonedible-oil sources with their utilization in diesel engines. For instance, some authors have reported on the potential of biodiesel production from *C. megalocarpus*[14–17] and *C. inophyllum*[18–21] as nonedible oils and *C. nucifera* (coconut)[22–25] as an edible oil.

Kivevele et al.[26] studied the engine performance and exhaust emissions of *C. megalocarpus* biodiesel with antioxidants in a four-cylinder turbocharged direct-injection (TDI) diesel engine at various load conditions. The fuel samples were *C. megalocarpus* biodiesel (B_{100}), *C. megalocarpus* biodiesel dosed with 1000 ppm of pyrogallol antioxidant ($B_{100}+PY_{1000}$), B_{20} (20 % *C. megalocarpus* biodiesel and 80 % diesel), and diesel. They found that the brake-specific fuel consumption (BSFC) of diesel was approximately 14.24 % lower than that of B_{100} at full load. In addition, it was found that $B_{100}+PY_{1000}$ recorded a lower BSFC than the untreated biodiesel but still higher than diesel. This is due the lower heating value of B_{100} and $B_{100}+PY_{1000}$. Moreover, the higher density of biodiesel is also another reason for the higher BSFC. The result of the BSEC of diesel at full load was lower than that of B_{20}, $B_{100}+PY_{1000}$, and B_{100}. This is due to the lower heating value of biodiesel compared to diesel. The brake thermal efficiency (BTE) was higher for diesel than biodiesel. This was due to the higher BSFC, lower calorific value, and higher viscosity of biodiesel. The results of NO_x emission at full load were higher for $B_{100}+PY_{1000}$ compared to B_{100} by 1.5 %, but lower at intermediate loads (25, 50, and 75 %). However, both were higher than diesel. The emission of CO at full load (100 %) conditions showed that the B_{20}, B_{100}, and $B_{100}+PY_{1000}$ produced slightly higher CO emissions as compared to diesel. The results of total hydrocarbons (THC) showed that they decreased with increasing percentage biodiesel at all loads except for the idle stage. The smoke was lower for biodiesel at all loads than for diesel.

Aliyu et al.[27] studied the performance (BTE, BSFC, and exhaust temperature) and exhaust emissions (CO, HC, CO_2, NO_x, and O_2) of a diesel engine using *C. megalocarpus* (musine) biodiesel and its blends (B_5, B_{20}, B_{50}, and B_{100}) at various speeds and load conditions. The thermal-efficiency results indicated that 100 % *C. megalocarpus* methyl ester (CME) showed the worst thermal efficiency. The increase in biodiesel percentage in the blends decreases the calorific value of the blends. Therefore, the specific fuel consumption (SFC) also increases. It was found that the fuel consumption values of B_5, B_{20}, B_{50}, and B_{100} at 1380 rpm and 7.5 kW power were 2.65, 3.8, 4.7, and 4.7 % higher than that of diesel, respectively. The highest exhaust-gas temperature was recorded for B_{100} whereas the lowest exhaust temperature was recorded for diesel. The results of the exhaust emissions showed that CO, CO_2, and HC emissions were higher for the CME and blends but the smoke emissions and NO_x were lower in comparison to diesel.

Sahoo et al.[18] presented the results of engine performance fueled with *Jatropha*, Karanja (*Pongamia pinnata)*, and Polanga (*C. inophyllum*) biodiesel. They observed that the maximum increase in power is observed for a 50 % Jatropha/diesel blend at rated speed whereas the best BSEC improvement is observed with 20 % Polanga biodiesel (PB). Smoke emissions reduced with blends and increasing speed during full throttle performance test. During the throttle-test mode,

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it has been observed that blends with higher percentages of biodiesel tend to decrease the exhaust smoke substantially. A noticeable reduction in HCs and particulate matter (PM) is seen with biodiesel and their blends. However, there is a slight increase in CO and NO_x.

Sataynarayana and Muraleedharan[25] studied the emissions and performance of a diesel engine operated at 1500 rpm by using vegetable oil methyl ester including palm kernel (POB), rubber (ROB), and coconut oil (COB) methyl esters. Among the tested biodiesels the maximum efficiency recorded (at the optimum load of 4.1 kW) was 37.78% with POB compared to 36.19% for diesel. Other biodiesels such as COB and ROB recorded thermal efficiencies of 28.04 and 33%, respectively. COB showed a lower BTE compared to POB and ROB due to a higher viscosity and lower volatility. All biodiesels showed higher CO emissions at lower loads and lower CO emissions for operation at higher loads as compared to diesel fuel. The HC emissions were lower in comparison to diesel fuel at all loads. This was attributed to the higher oxygen content of the biodiesel, which motivated complete combustion. It was observed that the NO_x emissions were higher for all biodiesels as compared to diesel fuel operation (with the exception of ROB) at all loads.

Results and Discussion

Physicochemical properties of biodiesel methyl esters and their blends

A comparison between the properties of the *C. megalocarpus* oil and methyl ester is given in Table 1. The important physicochemical properties of *C. megalocarpus,* coconut, and *C. inophyllum* methyl esters (CMME, COME, and CIME) were compared with the ASTM D6751 standard specification. Moreover, the properties of the B_{10} and B_{20} blends were also determined and compared with the ASTM D7467 standard. The detailed physicochemical properties are shown in Table 2.

Table 1. Comparison of the properties of *C. megalocarpus* oil and *C. megalocarpus* methyl ester.

Property	*C. megalocarpus* oil	*C. megalocarpus* methyl ester
kinematic viscosity[a]	30.195	4.0566
dynamic viscosity[b]	27.46	3.5282
density[a]	909.4	869.7
flash point	270--280	178.5
cloud point	−8	−4
pour point	−8	−3
calorific value	39.198	39.534
oxidation stability	0.12	1.1
kinematic viscosity[b]	7.2746	1.662
viscosity index	219.7	266.4

[a] at 40 °C, [b] at 100 °C.

Engine performance

Fuel properties can play a significant role in the engine performance. Biodiesel has a major influence on engine performance due to its higher oxygen content, higher density, higher viscosity, lower heating value, and higher cetane number.[28]

In this study, the effect of *C. megalocarpus,* coconut, and *C. inophyllum* methyl esters on engine performance in terms of torque, brake power (BP), and BSFC was assessed. The following section will discuss the obtained results of these parameters.

Engine torque

The variation of the torque produced from diesel and B_{10} and B_{20} blends at different engine speeds is shown in Figure 1 for full load conditions. It has been observed that

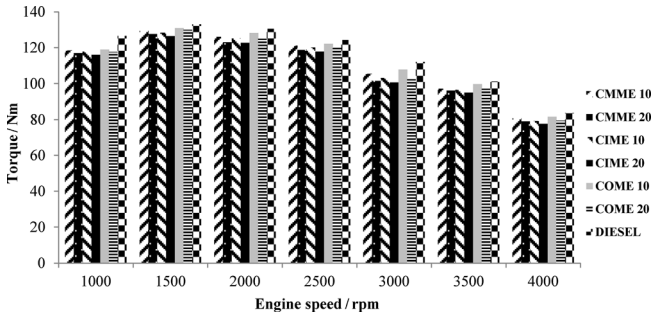


Figure 1. Variation of torque at different engine speeds and under full load conditions.

all torque values are lower for B_{10} and B_{20} as compared to diesel. Among all blends, it has been found that $COME_{10}$ gives the highest torque value of 130.9 N m at 1500 rpm as compared to 133 N m for diesel. $CIME_{20}$ gives the lowest torque value of 77.6 N m at 4000 rpm. Over the whole range of speed, the average torque values for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$, and diesel were found to be 111.12, 108.92, 109.98, 107.98, 112.7, 110.21, and 115.82, N m respectively. Thus, $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, and $COME_{20}$ give an average reductions in torque of 4.05, 5.95, 5.04, 6.77, 2.70, and 4.84%, respectively, compared to that of diesel. The reduction in torque values for all fuel blends is mainly attributed to the combined effect of their lower calorific value and higher viscosity compared to diesel fuel.[29–32]

Brake power

The variation of the brake power (BP) of diesel, B_{10}, and B_{20} at different engine speeds is shown in Figure 2 for full load conditions. In general, biodiesel–diesel blends produce lower brake power as compared to that of diesel fuel. Among all fuel blends, it has been found that $COME_{10}$ gives the highest BP value of 36.48 kW at 3500 rpm as compared to 36.99 kW

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Table 2. Physicochemical properties of CMME, COME, and CIME and their B_{10} and B_{20} blends.

Properties	Standard	ASTM D6751					*Croton*		*Calophyllum*		*Coconut*		ASTM D7467
			CMME	CIME	COME	Diesel	$CMME_{10}$	$CMME_{20}$	$CIME_{10}$	$CIME_{20}$	$COME_{10}$	$COME_{20}$	
kinematic viscosity[a] [$mm^2 s^{-1}$]	ASTM D445	1.9–6	4.0566	5.7499	4.0607	3.2333	3.4675	3.5023	3.4066	3.6105	3.2862	3.3427	1.9–4.1
dynamic viscosity[b] [MPa s^{-1}]	–	–	3.5282	5.0446	3.5182	2.6996	2.8954	2.9266	2.8575	3.0447	2.7542	2.8123	–
density[a] [kg m^{-3}]	ASTM D1298	860–900	869.7	877.4	866.4	827.2	831.2	835.6	838.8	843.3	838.1	841.3	–
flash point [°C]	ASTM D93	130 min	178.5	93.5	120.5	68.5	83.5	86.5	72.5	73.5	74.5	76.5	–
cloud point [°C]	ASTM D2500	Report	−4	10	0	8	6	5	8	8	7	7	Report
pour point [°C]	ASTM D97	–	−3	11	−4	0	0	0	1	1	0	−15	–
cold filter plugging point [°C]	ASTM D6371		−4	9	−4	5	7	7	7	6	7	7	–
calorific value [MJ kg^{-1}]	ASTM D240	–	39.534	39.273	38.006	45.304	44.90	44.23	44.578	44.065	44.532	43.748	–
iodine value [g_I/100 g]	EN 14111	120 max	155.5	87	9.4	–	–	–	–	–	–	–	–
saponification value	–	–	201	202	271.3	–	–	–	–	–	–	–	–
oxidation stability[c] [h]	EN ISO 14112	3	1.1	0.09	5.12	–	–	17.5	47.75	23.61	113.06	85.88	6 h min
cetane number	ASTM D613	47 min	38.5	53.7	64.3	–	–	–	–	–	–	–	40 min
kinematic viscosity[b] [$mm^2 s^{-1}$]	–	–	1.662	2.0344	1.5729	1.2446	1.3451	1.3718	1.315	1.3931	1.3084	1.3265	–
viscosity index	–	–	266.4	174.9	180.7	90	119.3	139.8	122.5	130.8	144.7	153.1	–

[a] at 40 °C, [b] at 100 °C, [c] at 110 °C.

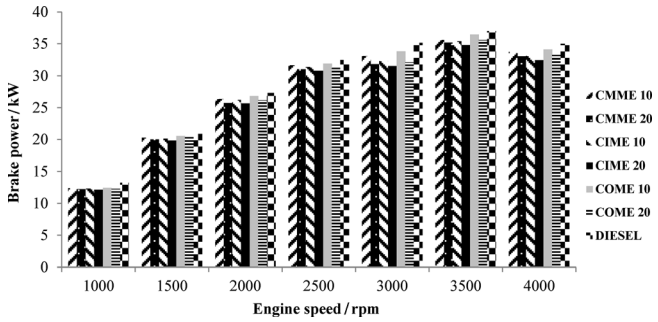


Figure 2. Variation of brake power at different engine speeds and under full load conditions.

for diesel. $CIME_{20}$ gives the lowest BP of 12.14 kW at 1000 rpm. The brake power increased gradually with engine speed; over the entire range of speed, the average BP values for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$, and diesel were found to be 27.59, 27.01, 27.27, 26.75, 28.02, 27.32, and 28.72 kW, respectively. $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, and $COME_{20}$ lowered the BP by 3.94, 5.95, 5.06, 6.85, 2.43, and 4.88 % as compared to diesel. This reduction is mainly owed to their lower heating values and higher viscosities as compared to diesel.[29,32,33]

Brake-Specific Fuel Consumption

The BSFC of diesel engine depends mainly on the relationship among the volumetric fuel injection system, fuel density, viscosity, and energy contents.[34] Figure 3 shows the variation of the BSFC of diesel and the B_{10} and B_{20} blends at different engine speeds under full load conditions. The BSFC values are higher for biodiesel blends at all engine speeds, and these findings are in agreement with those in literature.[35–37] Among all blends, it has been found that $COME_{10}$ gives the lowest BSFC value of 338.5 g kWh^{-1} at 1500 rpm as compared to 488 g kWh^{-1} for diesel. $CIME_{20}$ gives the highest BSFC value of 523.5 g kWh^{-1} at 4000 rpm. Over the entire

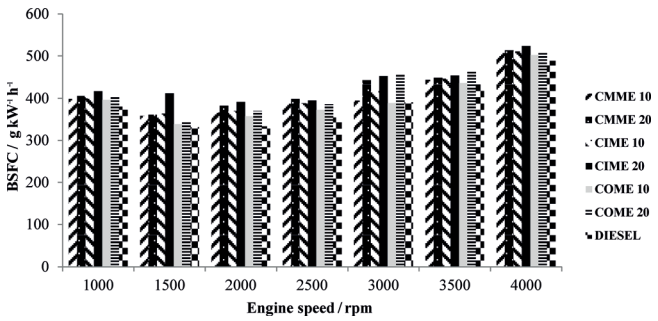


Figure 3. Variation of brake-specific fuel consumption at different engine speeds and under full load conditions.

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range of speeds, the average BSFC values for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$, and diesel were found to be 407.38, 421.34, 413.38, 434.58, 398.44, 419.44, and 386.85 $g\,kWh^{-1}$, respectively. $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, and $COME_{20}$ increased the BSFC by 5.3, 8.9, 6.85, 12.33, 2.99, and 8.31% in comparison to diesel fuel. The higher BSFC values of biodiesel blends are mainly due to the higher densities of the biodiesel–diesel blends.[29,38] Any fuel is delivered to the engine on a volumetric basis. For the same fuel volume, an increase in fuel density would imply a larger mass flow rate to the cylinders, and this would increase the BSFC to produce the same power.[39]

Emissions analysis

CO emissions

Carbon monoxide (CO) is a toxic gas formed from the incomplete combustion of any fuel that does not contain oxygen. Generally, several factors such as engine speed, air/fuel ratio, injection pressure, injection timing, and type of fuel have an effect on CO emissions.[24] Figure 4 shows the

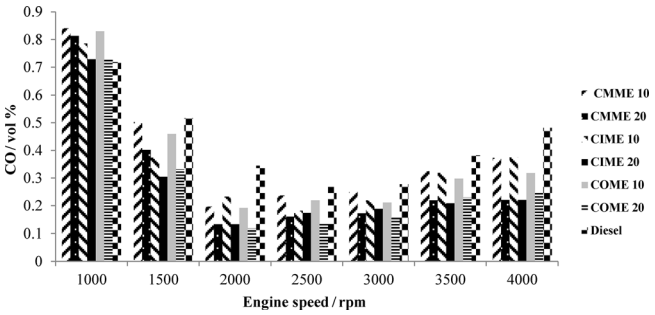


Figure 4. Variation of CO emissions at different engine speeds and under full load conditions.

variation of CO emissions of diesel (B_0), B_{10}, and B_{20} at different engine speeds and under full load conditions. Over the entire range of speeds, the fuel samples $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, and $COME_{20}$ give an average reduction of CO emission by 8.89, 29.04, 16.81, 34.49, 15.44, and 34.72% compared to B_0 fuel. These results are supported by literature.[38,40–43] This is due to the higher oxygen content of biodiesel (10–12% higher oxygen that diesel fuel) which results in a complete combustion. Therefore, as the percentage of biodiesel increased in the blend, the higher oxygen content of biodiesel allowed more carbon molecules to burn and the combustion became more complete. Moreover, low aromatics in the blends may be an additional reason for reduction in CO emissions.[29,44]

HC emissions

Unburned HCs mainly result from the incomplete combustion of fuel and flame quenching in crevice regions of the engine and at cylinder walls.[29] Figure 5 shows the variation

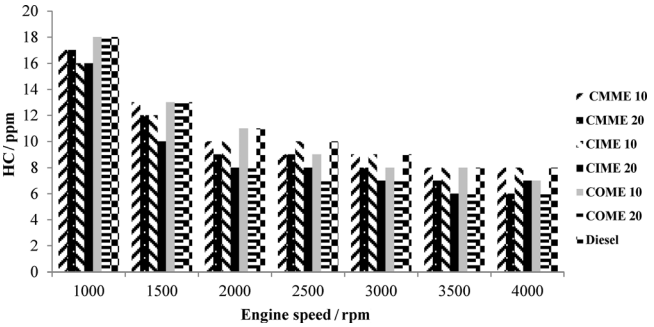


Figure 5. Variation of HC emissions with respect to engine speed under full load conditions.

of the HC-emission values of diesel (B_0), B_{10}, and B_{20} at different engine speeds and under full load condition. It is evident that unburned hydrocarbons for biodiesel–diesel blends are lower than that of diesel. Over the entire range of speed, the average reductions in HC emissions for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, and $COME_{20}$ as compared to diesel fuel are 3.89, 11.68, 5.19, 19.48, 3.89, and 15.58%, respectively. It can be also seen that the HC emissions are reduced as the percentage of biodiesel in the blends increases. This can be attributed to the higher cetane number and oxygen content and the lower carbon and hydrogen content of the biodiesel, which resulted in a more complete combustion.[44–46]

NO emission

The variation of the NO emissions of diesel and biodiesel–diesel blends is shown in Figure 6. It is seen that the NO values are somewhat higher for $CMME_{10}$, $CMME_{20}$, $COME_{10}$, and $COME_{20}$, consistent with the observations in the literature.[32] In contrast, using *C. inophyllum* biodiesel blends resulted in lower NO emissions, and the same observation was reported by Sahoo et al.[21] Over the entire range of speed, the average increase in NO emissions for $CMME_{10}$, $CMME_{20}$, $COME_{10}$, and $COME_{20}$ as compared to diesel were 7.31, 8.06, 1.55, and 6.16% respectively. The increase in NO emissions for these blends is attributed to the following reasons:[32,47]

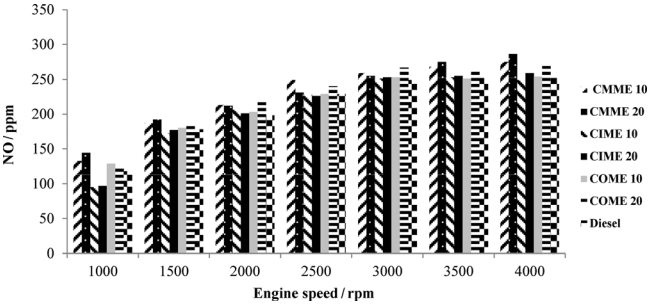


Figure 6. Variation of NO emissions at different engine speeds and under full load conditions.

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(1) Biodiesel is an oxygenated fuel that contains 11–12% more oxygen in its molecular structure. This causes higher adiabatic flame temperatures and helps to achieve more complete combustion and therefore higher NO emissions for biodiesel blends.
(2) Biodiesel naturally contains more double-bonded molecules than diesel. These double-bonded molecules have slightly higher adiabatic flame temperatures, which cause the increase in NO emissions for biodiesel blends.
(3) Radiation from soot formation in the flame zone is a major source of heat transfer away from the flame, and therefore it can lower bulk flame temperatures by 25–125 K, depending on the amount of soot produced at the engine operating conditions.

However, it has been observed that the average NO emissions for $CIME_{10}$ and $CIME_{20}$ blends were 0.54 and 1.49% lower than diesel fuel, respectively. This can be mainly attributed to the lower combustion-chamber temperatures observed with *C. inophyllum* biodiesel.[21]

Conclusions

As a renewable energy source biodiesel has caught the attention of researchers to be considered as a viable candidate to decrease greenhouse-gas emissions and dependency on imported fossil fuels as well as to meet the global energy demand.

This study presents the physical and chemical properties of coconut, *Calophyllum inophyllum*, and *Croton megalocarpus* methyl esters together with their 10 and 20% (*v*/*v*) blends (B_{10} and B_{20}). This is followed by evaluating their 10 and 20% blends in a multicylinder Mitsubishi Pajero diesel engine.

Based on the experimental study, the following conclusions can be drawn:

- The properties of *Croton megalocarpus,* coconut, and *Calophyllum inophyllum* biodiesel fuels and their blends agree with ASTM D6751 and ASTM D7467 standards, respectively.
- Over the entire range of speed, B_{10} and B_{20} blends of CMME, CIME, and COME result in an average reduction in torque, reduction in brake power (BP), increase in brake specific fuel consumption (BSFC) as compared to pure diesel (B_0). The fuel blends also give an average reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions. However, the CMME and COME blends increased the emissions of nitrogen oxides (NO) whereas CIME produced lower NO compared to B_0.

Finally, it can be concluded that CMME, CIME, and COME and their B_{10} and B_{20} blends can be used as diesel fuel substitutes with no modifications.

Experimental Section

Materials and chemicals

C. megalocarpus oil and *C. inophyllum* and coconut methyl esters were supplied from a local laboratory source. Table 3 shows the physicochemical properties of *C. megalocarpus* oil in comparison with crude canola, coconut, and *C. inophyllum* oils.[10] All other chemicals, reagents, and accessories were purchased from a local market.

Table 3. Properties of *C. megalocarpus* oil.[a]

Properties	*Croton*	*Canola*[10]	Coconut[10]	*Calophyllum*[10]
kinematic viscosity[b] [$mm^2 s^{-1}$]	30.195	35.706	27.640	55.677
kinematic viscosity[c] [$mm^2 s^{-1}$]	7.2746	8.5180	5.9404	9.5608
dynamic viscosity[b] [mPa s]	27.46	32.286	25.123	51.311
density[b] [$kg m^{-3}$]	909.4	904.2	908.9	N/D[a]
density[c] [$kg m^{-3}$]	927	N/D	N/D	951
specific gravity[c]	0.9278	N/D	N/D	0.952
acid value [mg_{KOH}/g_{oil}]	10.52	N/D	N/D	41.74
cloud point [°C]	−8	N/D	N/D	N/D
pour point [°C]	−8	N/D	N/D	N/D
flash point [°C]	270–280	290.5	264.5	236.5
calorific value [$MJ kg^{-1}$]	39.198	39.751	37.806	38.511
oxidation stability[e] [h]	0.12	5.64	6.93	0.23
viscosity index	219.7	213.5	168.5	165.4
transmission [%]	88.4	62.9	91.2	34.7
absorbance	0.054	0.202	0.04	0.46

[a] N/D: not determined, [b] at 40 °C, [c] at 100 °C, [d] at 15 °C, [e] at 110 °C.

Equipment

The equipment used in this study to measure the important physical and chemical properties is shown in Table 4.

Determination of cetane number, iodine value, and saponification value

The cetane number (*CN*), iodine value (*IV*), and saponification number (*SN*) were determined empirically by using the following equations:[29,48,49]

$$SN = \mathrm{SUM}\left(\frac{560 \times A_i}{MW_i}\right) \quad (1)$$

$$IV = \mathrm{SUM}\left(\frac{254 \times D \times A_i}{MW_i}\right) \quad (2)$$

$$CN = \left(46.3 + \left(\frac{5428}{SN}\right) - (0.225 \times IV)\right) \quad (3)$$

in which A_i is the percentage of each component, D is the number of double bonds, and MW_i is the molecular mass of each component.

Biodiesel production method from C. megalocarpus

The high acid value of *C. megalocarpus* oil inhibits the use of the unaltered alkaline-catalyzed process. Therefore, a two-step process (acid–base catalyst) was recommended to reduce the high

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Table 4. Summary of the apparatus used to measure the properties.

No.	Property	Equipment	Manufacturer	Test method
1	kinematic viscosity	SVM 3000	(Anton Paar, UK)	ASTM D445
2	density[a]	SVM 3000	(Anton Paar, UK)	ASTM D1298
3	density and specific gravity[b]	DM40	(Mettler Toledo, Switzerland)	
4	oxidation stability	873 Rancimat	(Metrohm, Switzerland)	EN ISO 14112
5	flash point	Pensky-martens flash point–automatic NPM 440	(Norma lab, France)	ASTM D93
6	cloud and pour point	cloud and pour point tester–automatic NTE 450	(Norma lab, France)	ASTM D2500, ASTM D97
7	cold filter plugging point	cold filter plugging point tester–automatic NTL 450	(Norma lab, France)	ASTM D6371
8	caloric value	C2000 basic calorimeter	(IKA, UK)	ASTM D240
9	viscosity index	SVM 3000	(Anton Paar, UK)	N/A
10	transmission and absorbance	Spekol 1500	(Analytical Jena, Germany)	N/A

[a] at 40 °C. [b] at 15 °C.

Table 5. Summary of biodiesel production process from *C. megalocarpus* oil.

No	Process parameter	Process specification
1	process type	acid–base catalyzed transesterification
2	reaction temperature	60 °C for both processes
3	catalyst used and concentration	98% pure sulphuric acid (1% *v*/*v*) for esterification reaction & 99% pure potassium hydroxides (1%, *w*/*w*) for transesterification reaction
4	alcohol used and molar ratios	(methanol) 12:1 for esterification process and 6:1 for transesterification process
5	reaction time	3 h for esterification process and 2 h for transesterification process
6	setting time	24 h
7	stirring speed	600 rpm

acidity of the crude oil; the first stage is used to decrease the free-fatty-acid content to a level safe enough for alkaline transesterification, and the esterified oil is converted into methyl ester in the second stage. The production of biodiesel was conducted at the energy lab of University Malaya by using glass reactor (2 L, brand: Favorit) equipped with a reflux condenser, overhead stirrer (IKA EUROSTAR digital), thermometer, and sampling outlet. Table 5 shows the summary of biodiesel production process.

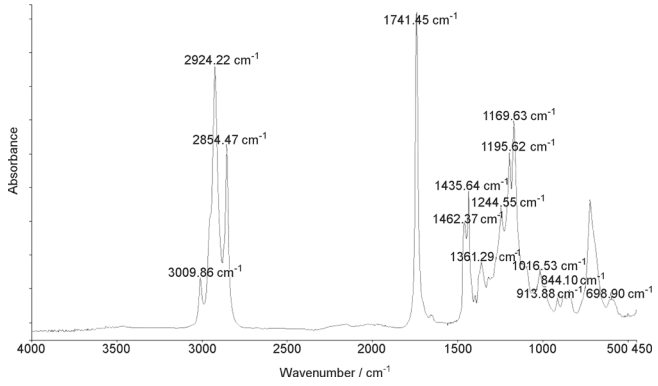


Figure 7. FTIR spectrum of CMME.

FTIR analysis of C. megalocarpus *methyl ester*

The FTIR analysis of *C. megalocarpus* methyl ester was perfrormed by using a PerkinElmer biodiesel FAME analyzer equipped with the MIR TGS detector in the range 4000–650 cm^{-1} and connected to the computer software program spectrum. The FTIR spectrum of the *C. megalocarpus* methyl ester is shown in Figure 7. The resolution was 4 cm^{-1} and 8 scans were performed. Table 6 shows the characteristics peaks of the *C. megalocarpus* methyl ester.

Gas chromatography (GC) method

The fatty acid compositions (FAC) profiles of coconut, *C. inophyllum*, and *C. megalocarpus* methyl esters were tested by using a gas chromatograph (Shidmadzu, Japan) equipped with a flame ionization detector. Table 7 shows the GC operating conditions. The results of the FAC are shown in Table 8. It can be seen that CMME is mainly dominated by linoleic acid (75.7%), COME is dominated by lauric acid (48.3%) and myristic acid (16.4%), and CIME is dominated by oleic acid (41.9%) followed by linoleic acid (26.2%). Saturated fatty acids represent 91.3% of COME. Unsaturated fatty acids represent 98.5 and 69.6% of CMME and CIME, respectively.

Table 6. Characteristics peaks of *C. megalocarpus* methyl ester in FTIR.

Absorption bands [cm^{-1}]	Functional group	Absorption intensity
3009	C–H stretching vibration	strong
2854–2924	$-CH_2-$ asymmetric and symmetric vibration	strong
1741	C=O stretching vibration	strong
1435–1462	$-CH_2-$ shear type vibration	moderate
1361.15	$-CH_3$ bending vibration	moderate
1169–1195	C–O–C symmetric stretching vibration	moderate
1016	C–O–C antisymmetric stretching vibration	weak
844	epoxy ring vibration	moderate
722	$-CH_2-$ plane rocking vibration	weak

Biodiesel–diesel blending

The biodiesel samples were blended with diesel at 10 and 20% (*v*/*v*) by using a magnetic stirrer (IKA C-MAG HS 7) at

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Table 7. GC operating conditions.

Property	Specifications
carrier gas	helium
linear velocity	24.4 cm sec^{-1}
flow rate	1.10 mL min^{-1} (column flow)
detector temperature	260.0 °C
column head pressure	56.9 kPa
column dimension	BPX 70, 30.0 m × 0.25 μm × 0.32 mm ID^{-1}
injector	240.0 °C
column oven	–
temperature ramp	140.0 °C (hold for 2 min) 8 °C min^{-1} 165.0 °C 8 °C min^{-1} 192.0 °C 8 °C min^{-1} 220.0 °C (hold for 5 min)

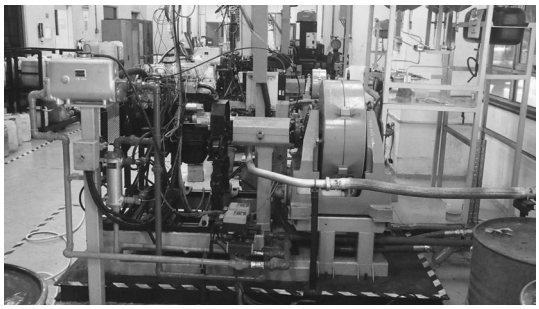


Figure 8. Engine test bed setup.

Table 8. Fatty acid composition of COME, CIME, and CMME.

No.	Fatty acid	Molecular weight [g mol^{-1}	Structure	Systematic name	Formula	CMME [%]	COME [%]	CIME [%]
1	caprylic	144	8:0	octanoic	$C_8H_{16}O_2$	0	8.2	0
2	capric	172	10:0	decanoic	$C_{10}H_{20}O_2$	0	6.6	0
3	lauric	200	12:0	dodecanoic	$C_{12}H_{24}O_2$	0	48.3	0
4	myristic	228	14:0	tetradecanoic	$C_{14}H_{28}O_2$	0.1	16.4	0
5	palmitic	256	16:0	hexadecanoic	$C_{16}H_{32}O_2$	6.3	9.3	14.4
6	palmitoleic	254	16.1	hexadec-9-enoic	$C_{16}H_{30}O_2$	0.1	0	0.3
7	stearic	284	18:0	octadecanoic	$C_{18}H_{36}O_2$	3.7	2.4	15.2
8	oleic	282	18:1	cis-9-octadecenoic	$C_{18}H_{34}O_2$	10.6	7	41.9
9	linoleic	280	18:2	cis-9-cis-12 octadeca-dienoic	$C_{18}H_{32}O_2$	75.7	1.7	26.6
10	linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	3.1	0	0.2
11	arachidic	312	20:0	eicosanoic	$C_{20}H_{40}O_2$	0.4	0	0.8
12	gondoic	310	20:1	11-eicosenoic acid	$C_{20}H_{38}O_2$	0	0	0.2
13	erucic	338	22:1	(*Z*)-docos-13-enoic acid	$C_{22}H_{42}O_2$	0	0	0.5
saturated						10.5	91.3	30.4
monounsaturated						10.7	7.0	42.8
polyunsaturated						78.8	1.7	26.8
total						100	100	100

Table 9. Technical specifications of the engine.

engine type	4 cylinder in-line
displacement [L]	2.5
cylinder bore *x* stroke [mm]	92 × 96
compression ratio	21:1
maximum engine speed [rpm]	4200
maximum power [kW]	55
fuel system	distribution type jet pump (indirect injection)
lubrication System	pressure feed
combustion chamber	wwirl type
cooling system	radiator cooling
A/F ratio	26

2000 rpm for half an hour and a shaker (IKA KS 130 basic) at 400 rpm for half an hour to make sure the blends were well blended.

Engine tests

The engine used in this study is a Mitsubishi Pajero (model 4D56T) multicylinder diesel engine. Table 9 shows the technical specifications of the engine. The test rig of the engine is shown in Figure 8. Figure 9 shows the schematic diagram of the engine setup. The engine test conditions were monitored by using a controller (REO-DCA) connected through a desktop computer to the engine test bed (Figure 9). To measure the exhaust emissions of NO, HCs, and CO, a BOSCH exhaust gas analyzer (model BEA-350) was used. The details of the exhaust gas analyzer are shown in Table 10. To produce average values, all tests were repeated three times.

The experimental investigation was performed by using diesel (B_0), B_{10} (90% diesel and 10% biodiesel), and B_{20} (20% biodie-

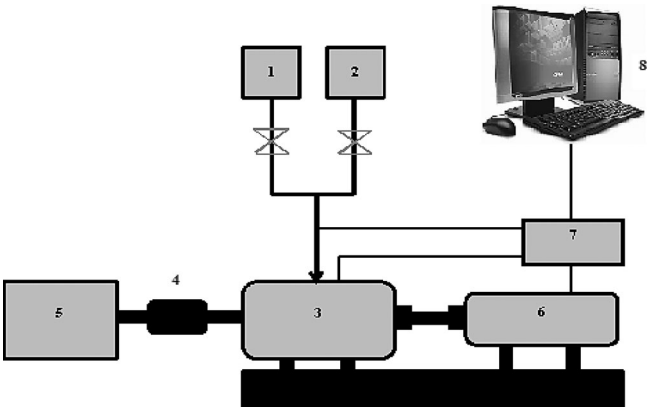


Figure 9. Diagram of the experimental setup for the engine test rig. 1: Fuel tank for neat diesel, 2: Fuel tank for the blends of diesel and biodiesel, 3: Mitsubishi Pajero (model 4D56T) multicylinder diesel engine, 4: Exhaust manifold, 5: BOSCH exhaust gas analyzer (model BEA-350), 6: Dynamometer, 7: REO-DCA controller), 8: Desktop computer.

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Table 10. Details of the exhaust gas analyzer.

Equipment	Method	Measurement	Upper limit	Accuracy	Percentage uncertainties
BOSCH gas analyzer	nondispersive infrared	CO	10.00 vol%	±0.001 vol%	0.002 vol%
	nondispersive infrared	CO_2	18.00 vol%	±0.001 vol%	0.150 vol%
	flame ionization detector (FID)	HC	9999 ppm	±1 ppm	2 ppm
	electrochemical transmitter	NO	5000 ppm	±1 ppm	21 ppm

sel and 80% diesel) blends, respectively. Firstly, the engine was run with diesel for 15 min to warm up the engine before running with B_{10} and B_{20} blends. The engine was run again with diesel before the engine was shut down. The same procedure was maintained for all fuel blends (CMME, CIME, and COME). This is very important to make sure that the engine is free from biodiesel blends before proceeding to the next performance. The engine was run at various speeds ranging from 1000 to 4000 rpm under full load conditions.

Nomenclature

ASTM	American Society for Testing and Materials
BP	brake power
BSFC	brake specific fuel consumption
BSEC	brake specific energy consumption
BTE	brake thermal efficiency
CMME	*Croton megalocarpus* methyl ester
CO	carbon monoxide
COME	coconut methyl ester
CIME	*Calophyllum inophyllum* methyl ester
FAC	fatty acid composition
HC	hydrocarbon
NO	nitrogen oxides
PM	particulate matter
rpm	revolutions per minute

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Keywords: biodiesel · biomass · emissions · engine performance · fuels

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