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Performance Evaluation of Single-Cylinder Diesel Engine Using Different Microemulsions of N-Butyl Alcohol, Coconut Oil and Diesel Fuel

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The use of n-butanol as surfactant allows the mixing of coconut oil and diesel fuel through microemulsification without any additional significant energy input compared with transesterification. This study evaluated the performance of a single-cylinder compression-ignition engine using different blends of n-butanol, coconut oil, and diesel. Four blends of fuel (D90-nB5-CO5, D80-nB10-CO10, D70-nB15-CO15, and D60-nB20-CO20) were formulated based on the available literature regarding the miscibility of the three fuel components. Each blend was evaluated at the engine's maximum rated output speed and maximum torque speed and compared with commercially available diesel (B5) through the varying load tests. Statistical analysis revealed that there were no significant differences in the power output, torque, fuel consumption, and oil and water temperatures between the blends and D100. Significant differences were observed among the blends at maximum output speed (6.18 kW) which were attributed to the higher oxygen content of blend D60. Significant differences were also observed between D100 (534.33°C) and the blends (420.67°C, 361.33°C, 356.00°C, and 435.67°C) in terms of exhaust gas temperatures which were attributed to the higher latent heat of vaporization of n-butanol which contributed to a cool-burn effect. Therefore, blends of up to 40% of 1:1 ratio of n-butanol and coconut oil mixed with diesel fuel can perform at par with the commercially available diesel fuel.

Key Words: biodiesel, cocodiesel, coco methyl ester, coconut oil, diesel fuel, n-butanol

INTRODUCTION

As one of the most abundant trees in the Philippines, the coconut (*Cocos nucifera*) has proven itself to be the tree of life. Benefits can be derived from its roots to the tip of its leaves. Aside from culinary, medicinal, and household uses, a coconut tree can also provide energy. The shells and husks are excellent sources of charcoal while the coconut meat provides coconut oil (Banzon 1980). Coconut oil is usually converted to biodiesel through transesterification, a process that involves the reaction of vegetable oil with alcohol to produce esters. Esters are chemical compounds wherein one or more hydroxyl groups are replaced by an alkoxyl group (IUPAC 2006).

Biodiesels derived from coconut oil are commonly known as coco-biodiesel or coco methyl ester (CME). CME can be a direct substitute or mixed in different proportions with conventional petroleum diesel to produce blends. Coco-biodiesels are known to have fewer emissions as they are biodegradable and contain zero sulfur as opposed to petroleum diesel fuel. Another advantage of coco-biodiesel is that it has a renewable source. The problem with biodiesels is that the transesterification process is costly (Diaz, undated). Bradley et al. (2006) noted that fueling diesel engines with raw coconut oil can be a better option since the availability of methanol, which is an ingredient for the transesterification process, is limited in some localities. The use of raw coconut oil skips the transesterification process and therefore reduces the cost of producing fuel. It is also a heat extensive process and therefore requires energy input which is usually provided by liquefied

Table 1. Percent volumetric composition of each fuel blend.

Fuel Blend	Diesel	Coconut	n-Butanol
D100	100	0	0
D90-Nb5-CO5	90	5	5
D80-Nb10-CO10	80	10	10
D70-Nb15-CO15	70	15	15
D60-Nb20-CO20	60	20	20
C10	90	10	0
C20	80	20	0
C30	70	30	0
C40	60	40	0

petroleum gas (LPG), another type of fossil fuel. Disadvantages of using raw coconut oil are viscosity problems at temperatures below 25°C and the need for purification process when used in unmodified engine (ASTAE 2009).

Microemulsion is another way of blending coconut oil and diesel without transesterification. This process requires a surfactant which allows two liquids of varying physical properties to be miscible. Higher chain alcohols with at least three carbon atoms and less than 21 hydrogen atoms are often used as surfactant for straight plant oil and diesel mixtures (Nair et al. 2010). N-butyl, one of the more commonly used surfactants, can be derived using renewable means. Without transesterification, blends formed by microemulsions can be cheaper since raw coconut oil will be used.

The results of this study can help shed light on the viability of using different microemulsified blends of n-butyl alcohol, coconut oil, and diesel fuel in a single-cylinder compression-ignition engine. The study focused on the evaluation of the diesel engine when fueled with ternary blends of the fuels using the varying load tests standardized in the Philippines for small engines. This study evaluated the engine performance in terms of power output, fuel consumption, and engine temperatures across different engine speeds.

MATERIALS AND METHODS

Preparation of Ternary/Microemulsified Blends

The formulation of the blends in this study was based on and limited to the information obtained from available literature pertaining to the miscibility of coconut oil, n-butanol, and diesel fuel (Nair et al. 2010).

Fifteen liters of n-butanol, about 30 L of crude coconut oil, and about 30 L of petroleum diesel were obtained from various commercial sources. The three fuel components were blended according to the ratios given in Table 1.

All the fuel blends were prepared using the splash-blending method, by simply adding n-butanol and coconut oil by percentage volume. The splash-blending of the three components did not require any stirring or agitation. In accordance with the Biofuels Act of 2006, all petroleum companies in the Philippines are mandated by law to sell diesel fuel with 5% CME by 2015. Consequently, all the diesel fuels obtained were B5 diesel. Six liters each of D100, D90-Nb5-CO5, D80-Nb10-CO10, D70-Nb15-CO15 and D60-Nb20-CO20 were prepared, while only 20 mL of D90-C10, D80-C20, D70-C30 and D60-C40 were prepared as the latter set of fuels were only used for sedimentation tests and not for engine performance tests.

The heating values of the four ternary fuel blends (D90-Nb5-CO5, D80-Nb10-CO10, D70-Nb15-CO15 and D60-Nb20-CO20) were determined based on ASTM D 4809 standards of the Energy Research and Testing Laboratory Services of the Department of Energy. The densities of all the fuels were determined using hydrometers. Temperatures of each fuel blend were also obtained for correction of readings. Cetane number and kinematic viscosity were determined based on formulas available from existing literatures. Cetane number was obtained using the equation:

$$CN_{TOT} = (C_D{*}CN_D) + (C_{CO}{*}CN_{CO}) + (C_{NB}{*}CN_{NB}) \quad \text{(Eq. 1)}$$

where CN_{TOT} is the total cetane number of the blend, CN_D is the cetane number of diesel, CN_{CO} is the cetane number of coconut oil, CN_{NB} is the cetane number of n-butanol, C_D is the volumetric concentration of diesel in the blend, C_{CO} is the volumetric concentration of coconut oil in the blend, and C_{NB} is the volumetric concentration of n-butanol in the blend.

For kinematic viscosity (Refutas' equation), viscosity blending index (VBi) was obtained using the equation:

$$VBi = 14.534{*}\ln(\ln(KVi + 0.8)) + 10.975 \quad \text{(Eq. 2)}$$

where VBi is the viscosity blending index of the component and KVi is the known kinematic viscosity of the component.

Table 2. Oxygen Composition of diesel, n-butanol, and coconut oil.

Fuel	C	H	O	Molecular Weight (kg/mol)	Oxygen Content (% weight)
Diesel	12	23	0	167.31	0
n-Butanol	4	10	1	74.12	21.5866163
Coconut oil	-	-	-	213.37	15.68010018
Composition:					
Lauric acid (47.5%)	12	24	2	95.15	7.59
Myristic acid (18.1%)	14	28	2	41.33	2.54
Palmitic acid (8.8%)	16	32	2	22.56	1.10
Caprylic acid (7.8%)	8	16	2	11.25	1.73
Capric acid (6.7%)	10	20	2	13.09	1.41
Oleic acid (6.2%)	18	34	2	17.51	0.70
Stearic acid (2.6%)	18	36	2	7.40	0.29
Linoleic acid (1.6%)	18	32	2	4.49	0.18
Caproic acid (0.5%)	6	12	2	0.58	0.14

Average viscosity blending index was obtained using the equation:

$$VBtotal = (W_D * VB_D) + (W_{CO} * VB_{CO}) + (W_{NB} * VB_{NB})$$ (Eq. 3)

where VBtotal is the total viscosity blending index of the blend, VB_D is the viscosity blending index of diesel, VB_{CO} is the viscosity blending index of coconut oil, VB_{NB} is the viscosity blending index of n-butanol, W_D is the volumetric concentration of diesel in the blend, W_{CO} is the volumetric concentration of coconut oil in the blend, and W_{NB} is the volumetric concentration of n-butanol in the blend.

Kinematic viscosity was computed as follows:

$$KV_{TOT} = ^{(eecVBi-10.975)/14.534)} - 0.8$$ (Eq. 4)

where KV_{TOT} is the kinematic viscosity of the blend, and VBi is the viscosity blending index of the blend.

The oxygen content (% wt) was computed using the molecular weight of oxygen in diesel, n-butanol, and coconut oil's fatty acid composition (Table 2).

A 5.97 kW (8 hp) single cylinder diesel engine was used in the study. This engine is commonly used as prime mover for two-wheel tractors as well as other stationary farm operations such as electricity generation and water pumping. Specifications of the engine are shown in Table 3.

Varying Load Test and Data Gathering

The engine's performance was determined following the varying load test procedure described in the Philippine Agricultural Engineering Standards (PAES) 117:2000 Small Engine – Methods of Test (AMTEC, 2000).

The experimental setup and equipment used are shown in Figures 1 and 2. The fuel consumption meter measured the time needed to consume 10 mL of fuel at a user-defined engine speed. The tachometer was used to measure the engine speed. A torque transducer coupled to a signal amplifier measured the torque produced. Three thermocouples connected to a digital read out panel displayed the temperature of the oil, water, and exhaust gases. Lastly, load switches coupled to a generator were used to vary the engine load and therefore vary the engine speed. All the data were averages of the readings obtained from three trial runs.

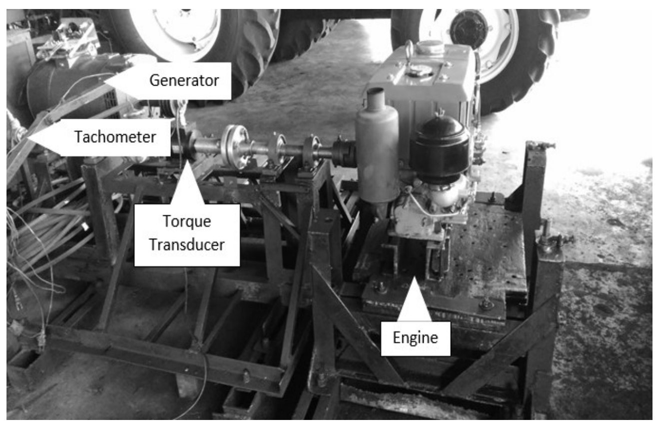

Fig. 1. Test engine mounted on the test rig.

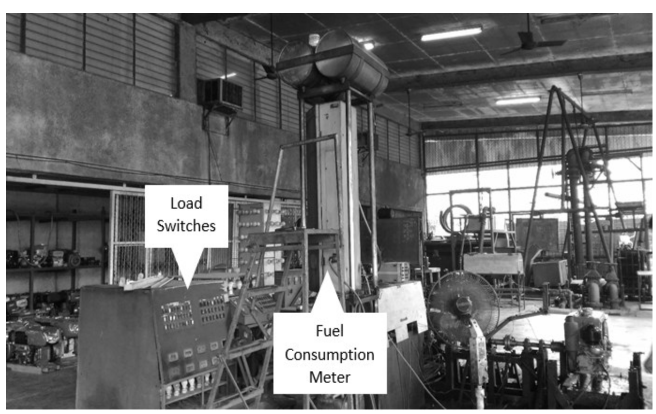

Fig. 2. Fuel consumption meter and the load switches.

Table 3. Specification of the 5.97 kW diesel engine.

Type	4-stroke horizontal single-cylinder engine
Bore × Stroke [mm]	82 x 84
Displacement [cm^3]	443
Continuous output [kW (hp) @ rpm]	5.22(7) @ 2200
Maximum output [kW (hp) @ rpm]	5.97(8) @ 2400
Maximum torque [kg-m @ rpm]	2.63 @ 1800
Compression ratio	18
Fuel	Light diesel
Nozzle opening pressure [kg cm^{-2}]	220
Combustion system	Direct injection
Cooling system	Water-cooled
Weight [kg]	79
Dimension (L x W x H) [mm]	714 x 353 x 466

RESULTS AND DISCUSSION

Characterization of the Fuel

Due to the lower heating values of n-butanol and coconut oil, the heating value was expected to decrease with decreasing diesel blend. Regression analysis gave a linear decreasing relationship as the concentration of diesel fuel decreased with the addition of 1:1 n-butanol and coconut oil. The line has a goodness of fit of 99.9% and is defined by the equation:

$$HV = 45.92 + 0.09910\ B \qquad \text{(Eq. 5)}$$

where HV is the heating value in Mj/kg, and B is the concentration of diesel in %.

As the density is affected by temperature, the readings were corrected using formulas from GOST R 8.610-2004, a Russian standard system specifically aimed at uniformity of measurements. The density of coconut oil increased the overall density of the blends as the percentage of coconut oil increased.

The increasing linear relationship with the addition of 1:1 n-butanol and coconut oil to the diesel fuel has a goodness of fit of 99.0% and is defined by the equation:

$$p = 832.2 + 0.2590\ B \qquad \text{(Eq. 6)}$$

where p is the density in kg/m3, and B is the concentration of diesel in %.

The cetane numbers of D100, the coconut oil and n-butanol were obtained from available literature while those of D90-Nb5-CO5, D80-Nb10-CO10, D70-Nb15-CO15 and D60-Nb20-CO20 were calculated by ratio and proportion based on the cetane number and the volume of the component fuels added to the blend.

The decreasing linear relationship of the cetane number with the amount of diesel fuel added with n-butanol and coconut oil has a goodness of fit of 100% and is defined by the equation:

$$CN = 54.00 + 0.1150\ B \qquad \text{(Eq. 7)}$$

where N is the cetane number, and B is the concentration of diesel in %.

The Department of Energy (2016) of the Philippines sets the minimum cetane number for Euro IV diesel fuels at 50. Based on the computed cetane number, blend D60 did not achieve the minimum required. The overall cetane number decreased as the blends increased due to the much lower cetane number of n-butanol.

The kinematic viscosity of the different blends was computed using Refutas equations which are commonly used in predicting viscosity of blends in the petroleum industry (Zhmud 2014). The linear increase in kinematic viscosity with increasing blends of n-butanol and coconut oil in diesel has a goodness of fit of 99.8% and is described by the equation:

$$KV = 3.050 + 0.02520\ B \qquad \text{(Eq. 8)}$$

where KV is the kinematic viscosity at 40°C in cSt, and B is the concentration of diesel in %.

The molecular weight decreased with decreasing diesel blend (Table 3). Unlike pure diesel, coconut oil and n-butanol have fuel bound oxygen atoms. These atoms are responsible for the reduction of air-to-fuel ratios as diesel blend decreases. Park et al. (2016) noted that soot formation decreases with increasing blends with fuel bound oxygen. The presence of oxygen within the fuel itself promotes better combustion and therefore reduces unburnt hydrocarbons. Table 3 also includes the oxygen content of the different blends.

Microemulsification prevents vegetable oils from forming sediments when combined with other fuels (Nair et al. 2010). The blends formulated in this study were compared with blends without n-butanol. After 7 d, sedimentation had occurred on each of the blends

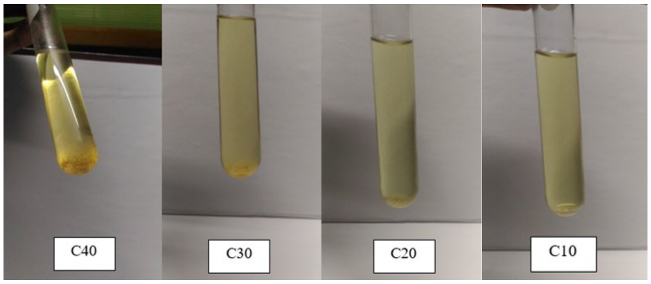

Fig. 3. Samples of blends C40, C30, C20, and C10 after 7d.

without n-butanol, the amount of which increased with increasing coconut oil in the blend (Fig. 3). This result showed that coconut oil and diesel mixtures are unstable mixtures which could lead to phase separation. Blends with n-butanol maintained clear mixture with no traces of sedimentation. The blends with n-butanol were observed to be stable or in single phase 7 d after formulation (Fig. 4).

Performance Evaluation

Output Power and Torque

Figure 5 shows the power outputs of different blends across different engine speeds. It also shows that there are minimal differences in terms of power throughout different speed settings. Figure 6 shows the differences in torque output of the different blends across different engine speeds. The output power and corresponding torque at the rated maximum output speed (2400 min^{-1})

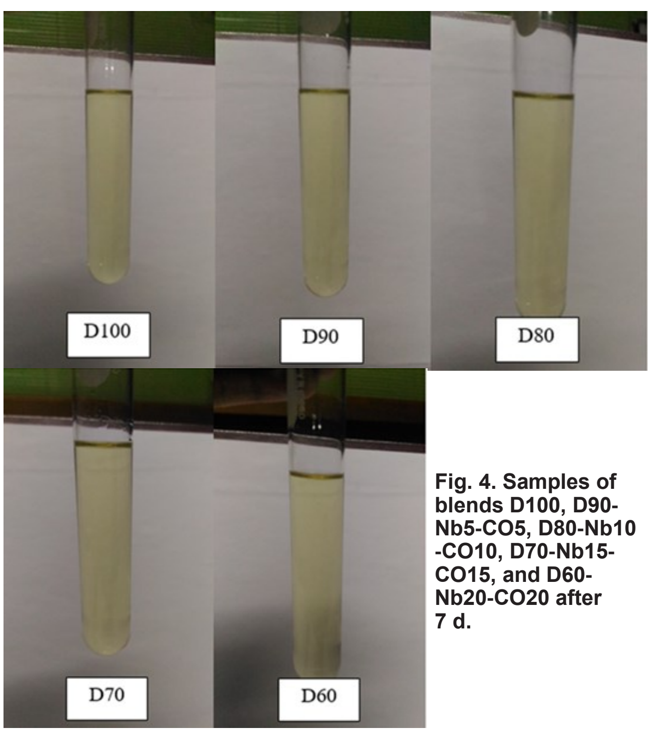

Fig. 4. Samples of blends D100, D90-Nb5-CO5, D80-Nb10-CO10, D70-Nb15-CO15, and D60-Nb20-CO20 after 7 d.

and the rated maximum torque speed (1800 min^{-1}) of the different blends are shown in Table 4.

For the manufacturer's rated maximum output power at 2400 min^{-1}, the highest power of 6.18kW was developed with blend D60, with a corresponding torque of 2.50 kg-m. The lowest maximum output power was developed with blend D80 at 6.04 kW and a corresponding torque of 2.45 kg-m. The manufacturer's rated power output at 2400 min^{-1} is 5.97 kW, indicating that all blends surpassed the rated power output.

For the manufacturer's rated maximum output torque at 1800 min-1, the highest torque developed was 2.72 kg-m, with blends D90 and D60 having corresponding power outputs of 4.96 kW and 4.95 kW, respectively. All the blends also surpassed the manufacturer's rated maximum torque of 2.63 kg-m.

Statistical analysis (ANOVA) performed on the maximum output power at 2,400 min^{-1} and corresponding torque showed that there are differences among the means obtained for each blend (P-value = 0.0295). Furthermore, using Tukey's HSD test, the maximum output powers developed by the D100, D90, and D70 blends were not significant compared with all the other blends. This result shows that the addition of 1:1 ratio of n-butanol and coconut oil up to 40% by volume will not affect the maximum power output of the engine.

On the other hand, blends D80 and D60 revealed a significant difference in means. D60 and D80 had the highest difference in power outputs for all the blends with a difference of about 140 watts. While it was expected that D60 would have the least amount of energy content, D60 registered the highest power output. This can be attributed to the greater amount of oxygen that came from higher concentrations of n-butanol and coconut oil which contributed to better atomization and combustion of the fuel (Swamy et al. 2015). Since the naturally-aspirated engine was not modified in any way, the air-to-fuel ratio delivery of the engine is maintained at all load settings (Rakopoulos et al. 2010). With the stoichiometric air-to-fuel ratio of D60 lower than that of D100, D60 requires less air to burn yet the air delivered is that for D100.

For the rated maximum torque, blend D90 achieved the highest torque at 2.72 kg-m while blends D100, D80, and D70 achieved the lowest torques at 2.68 kg-m. All blends surpassed the manufacturer's specified maximum torque of 2.63 kg-m at 1800 min^{-1}.

Table 4. Estimated characteristics of the different fuel blends.

Fuel Blend	Heating Value (MJ kg^{-1})	Corrected Hydrometer Reading (kg m^{-3})@ 30 °C	Cetane No.	Kinematic Viscosity (cSt) @ 40 °C	Oxygen (wt%)
D100	45.91[a]	832.4	54[c]	3.07[c]	0
D90-Nb5-CO5-	44.96	834.9	52.85	3.29	1.86
D80-Nb10-CO10	43.97	836.6	51.7	3.54	3.73
D70-Nb15-CO15	42.87	840.0	50.55	3.79	5.59
D60-Nb20-CO20	42.00	842.8	49.4	4.08	7.45
CO	38.68[b]	915.7	60[d]	27[f]	15.68
Nb	34.22[b]	801.8	25[e]	2.23[g]	21.59

[a]How et al. (2012)
[b]Singh et al. (2010)
[c]Petron Diesel Max (B5 POME) Product Data Sheet, n.d.
[d]Raturi, A. K., n.d
[e]Rakopoulos et al. (2016)
[f]ASTAE (2009)
[g]Atmanli et al. (2015)

Succeeding statistical analyses showed that the differences in the means of the maximum torque at 1800 min^{-1} were not significant (P-value = 0.6691). Based on statistical analyses, a 1:1 ratio of n-butanol and coconut oil can offset up to 40% diesel fuel without effects on the maximum torque of the engine.

Brake Thermal Efficiency

Brake thermal efficiency is a measure of how much energy is converted by the engine from chemical energy to useful mechanical work. It is taken as the ratio of the power output over the energy content of the fuel supplied. Therefore, a higher brake thermal efficiency is preferred due to its higher energy conversion rate. A high brake thermal efficiency also means that less fuel is converted to heat loss. Consequently, a high brake thermal efficiency decreases the amount of unburnt hydrocarbons. Table 6 displays the computed brake thermal efficiencies at maximum rated power and maximum rated torque settings.

The lowest brake thermal efficiencies were observed with blend D100 for both speed settings while the highest brake thermal efficiencies were observed with blend D60 for both speed settings. The higher brake thermal efficiencies of the blends as compared with pure diesel can again be explained by the extra oxygen molecules within the blends. Similar results were observed by Rakopoulos et al. (2010) and Dogan (2011). Dogan further emphasized that the increase in brake thermal efficiency could be attributed to the lower cetane rating of n-butanol blends. Lower cetane rating means a longer ignition delay period which promotes more fuel mixing period during the precombustion phase. This, along with the high laminar flame speed or the faster combustion of butanol, allows butanol blends to increase the amount of fuel burned even with lower cetane rating. However, further statistical analyses at the maximum output power (P-value = 0.088126) and maximum torque (P-value = 0.610395) revealed that the differences in brake thermal efficiencies were not significant for both speed settings.

Graphs of the brake thermal efficiencies of the different blends across different engine speeds are shown in Figure 7. The highest brake thermal efficiencies for all

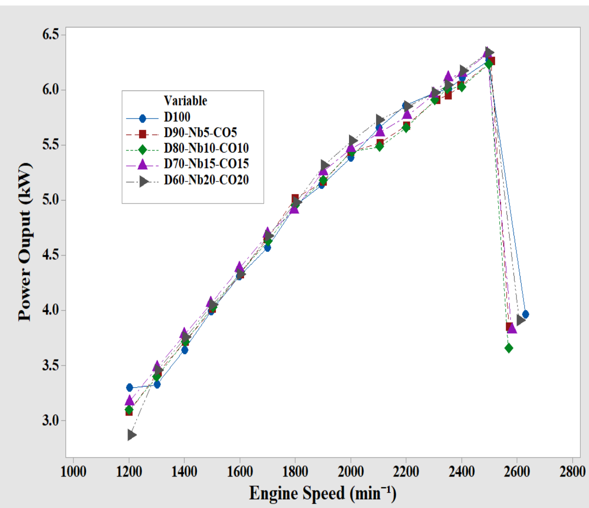

Fig. 5. Power outputs of different blends versus engine speed.

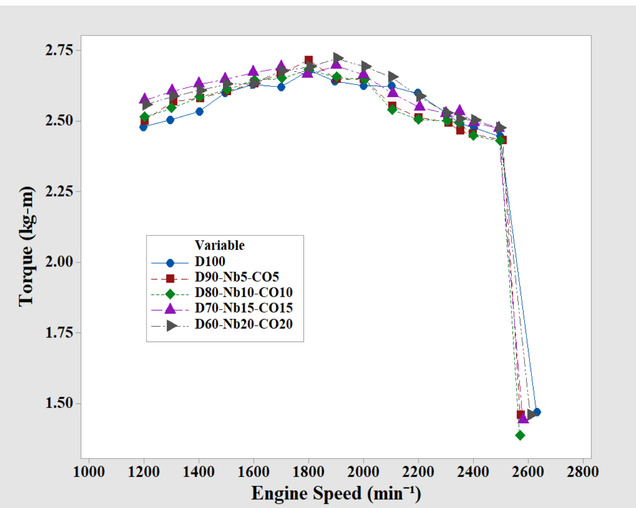

Fig. 6. Torque versus engine speed of the different blends.

Table 5. Average maximum output power at 2400 rpm and maximum torque at 1800 rpm.

Fuel Blend	Rated Maximum Output Speed: 2400 RPM		Rated Maximum Torque Speed: 1800 RPM	
	Power (kW)	Torque (kg m)	Power (kW)	Torque (kg m) ± 0.27
D100	6.11 ± 0.0016	2.48 ± 0.0050	4.96 ± 0.0016	2.68 ± 0.0061
D90-Nb5-CO5	6.05 ± 0.0054	2.46 ± 0.0067	5.02 ± 0.0014	2.72 ± 0.0200
D80-Nb10-CO10	6.04 ± 0.0012	2.45 ± 0.0081	4.95 ± 0.0014	2.68 ± 0.0317
D70-Nb15-CO15	6.15 ± 0.0022	2.49 ± 0.0117	4.94 ± 0.0020	2.68 ± 0.0230
D60-Nb20-CO20	6.18 ± 0.0019	2.50 ± 0.0044	4.97 ± 0.0017	2.69 ± 0.0172
ANOVA	Significant	Not significant	Not significant	Not significant

the blends were observed on full throttle setting with no load. After the application of load, brake thermal efficiencies significantly dropped. From the graph, it can be seen that blend D100 had the lowest brake thermal efficiency at almost all the speed settings. Blend D60 had the highest brake thermal efficiency at the high speed no load. The highest recorded brake thermal efficiency was observed with blend D90 at 25.61% at 2571 rpm while the lowest brake thermal efficiency was observed with blend D100 at 1201 rpm.

Fuel Consumption and Specific Fuel Consumption

Figure 8 shows the differences of the fuel consumption of the different blends across different engine speeds. From the graph, it can be seen that across engine speeds, blends D60 and D70 had higher fuel consumption. Between 1700 and 1600 min^{-1}, there is a big reduction in fuel consumption for blends D80, D90, and D100. Blend D70 had mostly higher fuel consumption in higher and lower engine speeds. Blend D90 performed best at higher speeds while at lower speeds, blends D100, D90, and D80 consumed the least fuel. Figure 8 shows the specific fuel consumption of the different blends across different engine speeds. At lower speeds, Blend D70 consumed the most fuel per output power while blend D80 consumed the least. At higher engine speeds, blend D70 also consumed more fuel per output power while blend D90 consumed less.

Table 6. Brake thermal efficiency at maximum power and maximum torque.

Fuel Blend	Rated Maximum Output Speed: 2400 RPM	Rated Maximum Torque Speed: 1800 RPM
	Brake Thermal Efficiency (%)	Brake Thermal Efficiency (%)
D100	13.39 ± 0.0003	13.27 ± 0.0015
D90-Nb5-CO5	14.72 ± 0.0043.	14.77 ± 0.0114
D80-Nb10-CO10	14.86 ± 0.0043	14.87 ± 0.0092
D70-Nb15-CO15	14.69 ± 0.0029	14.41 ± 0.0043
D60-Nb20-CO20	15.27 ± 0.0041	15.06 ± 0.0026
ANOVA	Not significant	Not significant

For the maximum output speed, the lowest fuel consumption obtained was from blend D90 with a consumption of 3.92 l h^{-1}. The highest fuel consumption was attained with blend D100 at 4.24 l h^{-1}. Consequently, the lowest specific fuel consumption was with blend D90 at 541.10 g kW^{-1} h^{-1} and the highest specific fuel consumption was with blend D100 at 578.09 g kW^{-1} h^{-1}. Further statistical analyses revealed that the increasing concentration of n-butanol and coconut oil does not affect fuel consumption (P-value = 0.1969) and specific fuel consumption (P-value = 0.4456).

Oil, Water and Exhaust Temperatures

Oil, water, and exhaust gas temperatures using different blends across different engine speeds are shown in Figures 10, 11, and 12, respectively. Generally, oil temperature and water temperature increased with increasing load. From Figures 10 and 11, it can be seen that blend D90 had the highest oil and water temperatures. For water temperature, there was a significant drop in temperature after achieving peak power before rising again for all blends. For exhaust gas temperatures (Fig. 12), the difference between D100 blend and all the other blends was observed to be significant. Peak exhaust gas temperatures occurred at different speed settings for some blends. For blends D100 and D90, peak exhaust temperature occurred near the peak power speed at 2400 min^{-1}. For

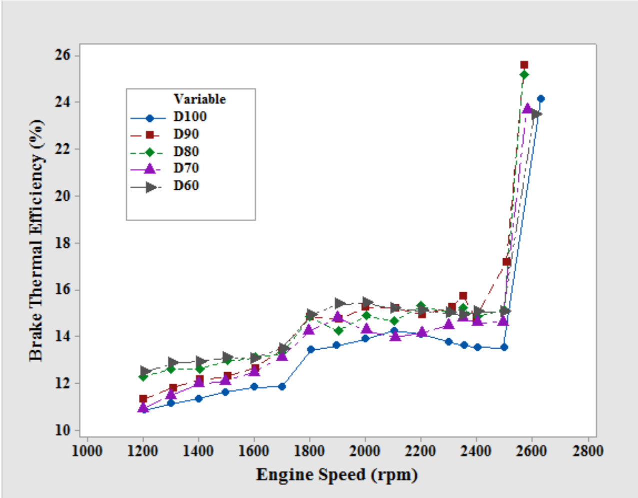

Fig. 7. Brake thermal efficiency versus engine speed of the different blends.

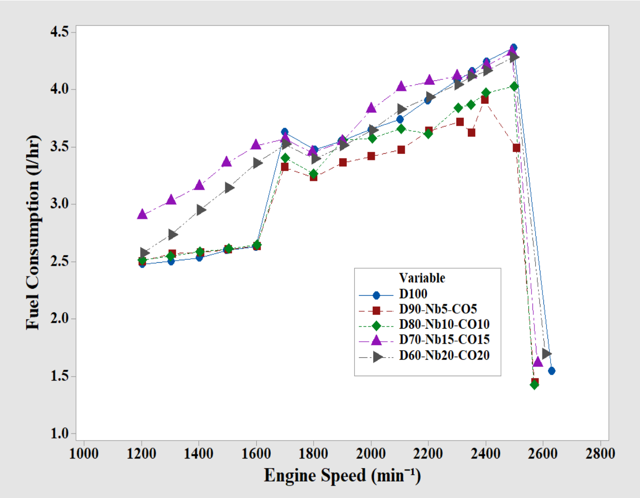

Fig. 8. Fuel consumption of the different blends versus engine speed.

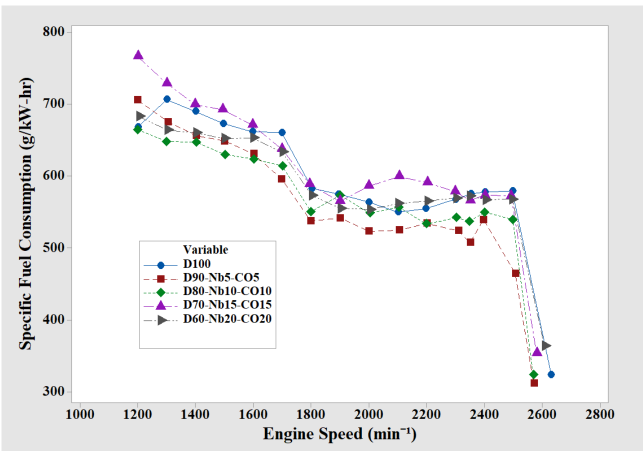

Fig. 9. Specific fuel consumption of the different blends versus engine speed.

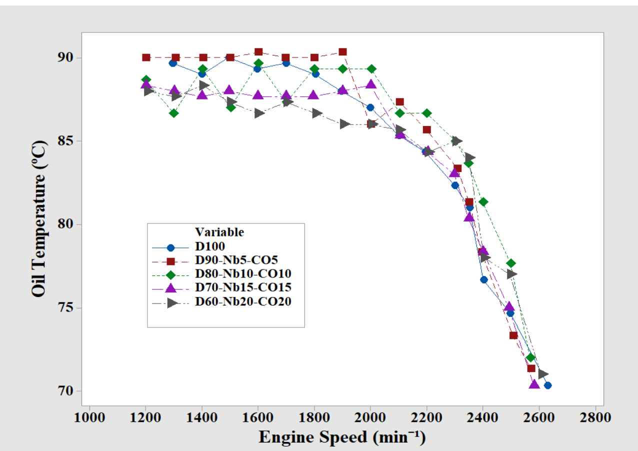

Fig. 10. Oil temperature of the different blends versus engine speed.

the rest of the blends, peak exhaust gas temperatures occurred around the peak torque mark at 1800 min^{-1}. The different temperatures that were recorded at the two speed settings are shown in Table 7.

Table 8 shows the oil, water, and exhaust gas temperatures of the different blends at 2400 min^{-1} and 1800 min^{-1}. Statistical analyses showed that there were no significant differences between the working oil and water temperatures across different blends in the maximum power output and maximum torque setting. The water temperature obtained was also within the specified range for diesel engines (Asuncion 2010). However, statistical analysis of the exhaust gas temperatures revealed significant changes in the means obtained from different blends for both the maximum output power (P-value = 0.0004) and maximum torque (P-value = 0.0007) setting. Tukey's HSD analysis showed that at maximum output power and maximum torque, the differences in exhaust gas temperatures between blend D100 and other blends were significant.

The lower heating value of the blends could cause lower exhaust gas temperatures. The higher latent heat of evaporation of n-butanol allows it to absorb more heat during combustion and therefore reduce exhaust gases (Doğan 2011). The higher oxygen content of both n-butanol and coconut oil compared with diesel also signifies a much "leaner" fuel blend due to the presence of oxygen within the fuel itself (Rakopoulos et al. 2011). This condition allows the engine to convert more fuel for power and less fuel is converted as waste heat. Different studies about n-butanol/diesel and n-butanol-vegetable oil-diesel blends have different results in terms of nitrous oxide emissions. Yilmaz et al. (2014) found that carbon monoxide emissions are reduced while nitrous oxide emissions are increased versus diesel fuel at 5% and 10%

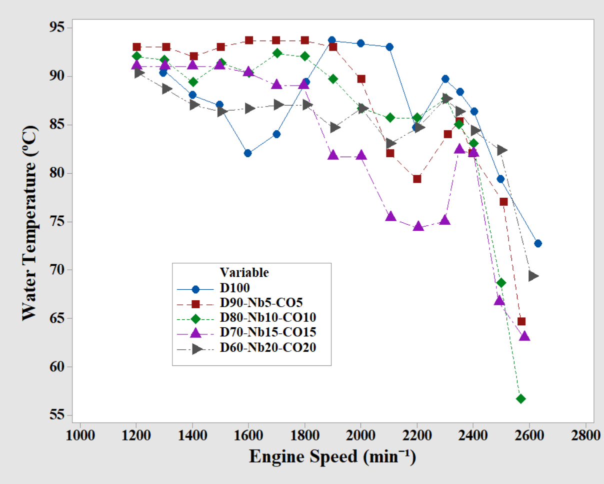

Fig. 11. Water temperature of the different blends versus engine speed.

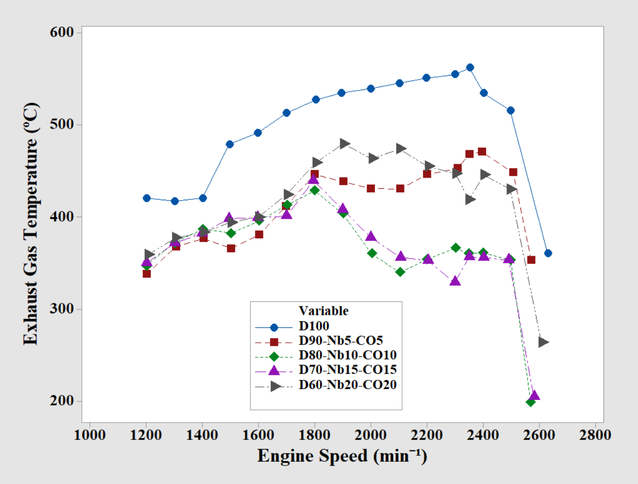

Fig. 12. Exhaust gas temperature of the different blends versus engine speed.

concentration of n-butanol against biodiesel. The opposite is true for 20% concentration of n-butanol. Doğan (2011) also suggested that the increase in oxygen content of n-butanol blending can increase probability of the oxygen molecule forming nitrous oxide. He also noted that the reduction in combustion temperature due to higher heat of evaporation helped prevent formation of nitrous oxides. In order to conclude that n-butanol and coconut oil blends reduce nitrous oxide emissions, actual gas analysis should be further conducted. However, there are disadvantages in terms of reduced exhaust gas temperature. High exhaust gas temperatures are needed for high pressure boosts as in the case of turbocharging (Nguyen-Schäfer 2015). Furthermore, exhaust gas temperatures directly affect the efficiency of catalytic converters which are used to reduce CO and hydrocarbon emissions. Higher temperatures increase the efficiency of catalytic converters by up to 95% (Shahbahkti et al. 2009). While the exhaust gas temperatures are significantly reduced for blends against diesel, output power differences were proven to be insignificant. It implies that the brake thermal efficiency slightly increased for the blends since there was no significant power loss with increasing blends of coconut oil and n-butanol.

CONCLUSION AND RECOMMENDATIONS

For this study, different microemulsions of diesel, coconut oil, and n-butanol were formulated based on information from existing literature. Each fuel blend was tested on a 5.94 kW compression ignition engine under a standard varying load test procedure. Results showed that there were no significant differences in the output power (at 1800 min^{-1}), torque, fuel and specific fuel consumption, oil and water temperature between blend D100 and all the other blends. However, significant differences in output power at 2400 min^{-1} were observed between blends D80 (6.04 kW) and D60 (6.18 kW) mainly

Table 7. Fuel consumption and specific fuel consumption at 2400 rpm and at maximum torque at 1800 rpm.

Fuel Blend	Rated Maximum Output Speed: 2400 RPM		Rated Maximum Torque Speed: 1800 RPM	
	Fuel Consumption ($L\ h^{-1}$)	Specific Fuel Consumption ($g\ kW^{-1}\ h^{-1}$)	Fuel Consumption ($L\ h^{-1}$)	Specific Fuel Consumption ($g\ kW^{-1}\ h^{-1}$)
D100	4.24 ± 0.02	578.09	3.48 ± 0.05	583.39
D90-Nb5-CO5	3.92 ± 0.10	541.10	3.29 ± 0.10	546.83
D80-Nb10-CO10	3.98 ± 0.12	551.60	3.29 ± 0.15	555.79
D70-Nb15-CO15	4.21 ± 0.06	574.07	3.46 ± 0.11	586.57
D60-Nb20-CO20	4.17 ± 0.10	568.31	3.40 ± 0.07	575.46
ANOVA	Not significant	Not significant	Not significant	Not significant

Table 8. Oil, water, and exhaust gas temperatures of the different blends at 2400 rpm and 1800 rpm.

Fuel Blend	Rated Maximum Output Speed: 2400 RPM			Rated Maximum Torque Speed: 1800 RPM		
	Oil Temp (ºC)	Water Temp. (ºC)	Exhaust Gas Temp. (ºC)	Oil Temp. (ºC)	Water Temp. (ºC)	Exhaust Gas Temp. (ºC)
D100	81.00 ± 1.44	88.33 ± 3.47	534.33 ± 12.06	89.00 ± 1.63	89.33 ± 2.42	527.00 ± 9.18
D90-Nb5-CO5	78.33 ± 0.54	82.00 ± 3.09	420.67 ± 7.52	90.00 ± 0.82	93.67 ± 0.72	396.33 ± 17.90
D80-Nb10-CO10	81.33 ± 1.96	83.00 ± 3.27	361.33 ± 16.29	89.33 ± 0.98	92.00 ± 0.72	428.67 ± 4.12
D70-Nb15-CO15	78.33 ± 0.54	82.00 ± 0.82	356.00 ± 11.43	87.67 ± 0.27	89.00 ± 1.25	439.33 ± 12.45
D60-Nb20-CO20	78.00 ± 0.82	84.33 ± 0.98	435.67 ± 25.80	86.67 ± 0.54	87.00 ± 0.82	458.67 ± 8.09
ANOVA	Not significant	Not significant	Significant	Not significant	Not significant	Significant

due to the latter's greater oxygen content. Significant exhaust temperature differences were also observed between blends D100 and all the other blends at maximum output speed (534.33°C against 420.67°C, 361.33°C, 356.00°C, and 435.67°C) and maximum torque speed (527.00°C against 396.33°C, 428.67°C, 439.33°C, and 458.67°C). However, there were no significant differences among the blends.

By replacing the composition of the diesel fuel of up to 40% 1:1 n-butanol and coconut oil, there were no significant differences between the diesel fuel in terms of output power, torque, fuel and specific fuel consumption, oil and water temperature. Therefore, the blends formulated performed at par with diesel based on the previous parameters. This result shows that the characteristics of the additional blend of n-butanol and coconut oil behaved similarly as the commercially available diesel fuel.

Further studies should measure emissions while performing varying load tests. Emissions were not tested in this study due to the lack of dedicated equipment. Also, further studies could revolve around the durability and reliability of engines fueled with different blends as well as a more thorough cost analysis on the formulation of the microemulsified fuel compared with the cost of using only biodiesel and diesel oil.

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