Emission Benefits from the Use of Castor Oil in a Compression Ignition Engine Fuelled with Diesel-Ethanol Blends

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***Abstract*—Castor oil which is produced from non-food crop and contains high proportion of ricinoleic acid was added to ethanol-diesel blend, forming the ternary blend. The extremely high viscosity and good lubricating properties of castor oil were expected to restore the substantial reduction in such fuel properties due to the presence of ethanol in the blend. The basic physical and chemical properties of the test fuels were measured according to ASTM standards and the engine test was conducted on a four-cylinder direct injection diesel engine with naturally aspirated and water-cooled system. The experimental results showed that the high viscosity, density, flash point of castor oil can help to improve the properties of the fuel blend due to some poor properties of ethanol leading to keep the fuel properties of the ternary blend under the limit of diesel fuel specifications. The emission benefits of the reduction in CO, NOx and smoke emissions were obtained by the combustion of the ternary blend without the significant increase in THC emissions at high engine operating loads, compared to diesel fuel combustion. It is evident that the incorporation of castor oil and ethanol as blend components to reduce the use of diesel fuel for compression ignition engines is a feasible alternative for next generation fuels.**

***Index Terms*—castor oil, ethanol, compression ignition engine**

I. Introduction

Alternative and renewable fuels have been proven to replace the use of conventional fuels in both spark ignition engines and compression engines. Among these fuels, advanced biofuels such as bioalcohol and second-generation biodiesel which are derived from waste, agriculture residues and non-food crops have been receiving more attention as sustainable alternative to fossil fuels. Oxygen present in fuel molecules of bioalcohol and biodiesel can participate in a cleaner combustion process, resulting in a reduction of engine-out emissions to meet increasingly stringent vehicle emission standards. Bioalcohol, especially ethanol and n-butanol, can be produced from waste or lignocellulosic materials through advanced production techniques such as acetobutylicum fermentation, genetic engineering of Clostridium thermocellum and Guerbet reaction, and can reduce the life-cycle greenhouse emissions which depends on biological production processes [1]-[3]. Although, alcohols are usually used in spark ignition engines there is an increasing interest in using them as blend component for diesel fuel in Compression Ignition (CI) engines [4]-[5]. Alcohol blends shows a potential way to decrease Particulate Matter (PM) emissions compared to diesel fuel, while may increase Total Hydrocarbon (THC) at low engine operating condition and there is no consensus about Carbon monoxide (CO) and Nitrogen Oxide (NOx) emissions [6]-[8]. However, some poor chemical and physical fuel properties of alcohols such as viscosity, cetane number, flash point, calorific value, miscibility and lubricity can limit the use of alcohol with high percentage in compression ignition engines.

To restore such poor fuel properties, biodiesel with the absence of aromatic content, higher viscosity, higher solubility with alcohol and higher flash point is an interesting option to use with alcohols for promoting new biofuels to replace the use of conventional fuels. Previous studies have reported that the presence of mixtures of several fatty acids in biodiesel, especially fatty acid with long carbon-chain length, tends to increase lubricating film thickness, resulting in the better lubricity of biodiesel. This will introduce a reduction in friction and wear of moving contact surfaces of fuel system components [9]-[11]. On the other hand, alcohol can improve the low temperature properties of biodiesel such as cold filter plugging point, cloud point, pour point and freezing point [12]. In term of emissions, a clear reduction in particulate matter emissions is obtained by the combustion of biodiesel while an increase in oxides of nitrogen is challenging for diesel engines operating with biodiesel [13], [14]. Therefore, the synergistic effect of the incorporation of alcohol and biodiesel may be found for developing new biofuels to meet increasingly stringent emission regulations.

Biodiesel derived from non-edible feedstock is more attractive to use as sustainable fuels in diesel engines to avoid the competition with human food or animal feed. Non-food crop and excellent lubricity are promising factors for castor oil as an alternative feedstock of biodiesel. Biodiesel derived from castor oil is a unique biodiesel with more oxygen atom of hydroxyl group

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compared to other biodiesel feedstocks. The major fatty acid composition of castor oil is ricinoleic acid (hydroxylated fatty acid). Extremely high viscosity of methyl ricinoleate (C18:1 OH) is caused to fail the use castor oil methyl ester (COME) as biodiesel fuel in diesel engines according to the European biodiesel standard, EN 14214. However, this drawback of castor oil is expected to recover a substantially reduction of viscosity due to the addition of alcohol to diesel fuel. The utilisation of COME as blend component to extend the use of alcohol-diesel blend were studied in previous works [15], [16]. The results showed that the combination of alcohols with COME improved the most relevant fuel properties of the blends which influence the combustion process closer to diesel fuel. The presence of the hydroxyl group in both alcohol and COME was to be beneficial in terms of engine-out emissions which the improvement of NOx-soot trade-off was obtained.

Instead of studying the effect of biodiesel on the diesel-ethanol blends, the addition of crude castor oil to ethanol blends was investigated in this study. The basic physical and chemical properties of the tested fuels were measured according to ASTM standards and engine experiments were conducted to evaluate the combustion and engine-out emissions of the triblends (diesel-ethanol-castor oil) compared to diesel fuel combustion.

II. Materials and Methods

A. Test Fuels

The presence of 10% of anhydrous ethanol by volume in the diesel fuel was selected to study the effect of castor oil on fuel properties, combustion characteristics and engine-out emissions. With preliminary work on lubricity experiment, the addition of 10% castor oil was enough to restore the lubricity of the ethanol blends, there was no significant improvement on the blend lubricity after this percentage of castor oil. Consequently, the fuel blend of 10% castor oil, 10% ethanol and 80% diesel fuel (D80E10C10) was used to operate with the engine. The fatty acid profile of castor oil was detailed in Table I and it can be confirmed that the majority of fatty acid present in castor oil is ricinoleic acid with more than 85% wt. The basic physical and chemical properties of test fuels were measured according to ASTM standards and was shown in Table II.

TABLE I. Fatty Acid Profiles of Castor Oil

Fatty acid		% wt
Lauric	C12:0	0.02
Myristic	C14:0	0.06
Palmitic	C16:0	1.63
Stearic	C18:0	1.66
Oleic	C18:1	3.85
Ricinoleic	C18:1 OH	85.6
Linoleic	C18:2	6.04
Linolenic	C18:3	0.43
Arachidic	C20:0	0.08
Gadoleic	C20:1	0.58
Eicosadienoic	C20:2	0.05

TABLE II. Basic Physical and Chemical Properties of Test Fuels

Fuel Properties	Units	Test Method	Diesel	Ethanol	Castor oil	D80E10C10
Kinematic viscosity @40 ℃	cSt	ASTM D445	3.54	1.26	289	4.06
Flash point	℃	ASTM D93	78	13.5	282	158
Specific gravity @15.6 ℃	-	ASTM D1298	0.828	0.785	0.950	0.836
Density @15.6 ℃	kg/m^3	ASTM D1298	827.2	784.2	949.1	835.2
Cetane index	-	ASTM D976	60.18	8^{CN}	48^{CN}	55.2
Gross Calorific Value	(MJ/kg)	ASTM D240	45.39	26.83	36.16	42.23

B. Experimental Setup for Engine Test

A four-cylinder direct injection diesel engine with naturally aspirated and water-cooled system was used for the engine test to evaluate combustion characteristics and exhaust emissions of the triblend fuel, which were compared to that of diesel fuel. The engine specification is shown in Table III. The experimental installation is drawn schematically in Fig. 1. A hydraulic dynamometer equipped with a load cell was used to load the engine. The engine was tested at 2000 and 2500 rpm with varying five engine operating loads (30, 50, 70, 90 and 110 N.m) which represents the range of the engine operating condition from low to high levels. A Kistler 6052C pressure transducer mounted at glow plug adapter and connected via a Kistler 5064C charge amplifier to a data acquisition board was employed to record in-cylinder pressure traces. To calculate the combustion chamber volume at any crank angle, a Kistler 2164CK1 crank angle encoder set was mounted on the crankshaft adapter to measure the crankshaft position. Other standard engine test rig instrumentations were installed to monitor temperatures (intake air and exhaust gas), pressure (lubricating oil), humidity (intake air) and mass flow rate (intake air and fuel). Engine-out emissions were measured by standard exhaust gas analysers: Testo 350 for CO and NOx, Horiba Mexa-584L for HC and Testo 308 for smoke emissions. In each condition tested, the engine was stabilized by the observation of exhaust temperatures and exhaust emissions.

TABLE III. SPECIFICATION OF TEST ENINGE

Engine type	4-Stroke, 4 - Cycle, Direct Injection, Water Cooled, Naturally aspirated
Number of cylinder – Bore x Stroke	4 – 93.0 x 92.0 mm.
Total piston displacement	2.449 m^3
Compression ratio	18.4
Fuel injection timing (bTDC)	14°
Rated power	64.9 kW @4000 rpm
Max.Torque	171.5 N-m @2000 rpm

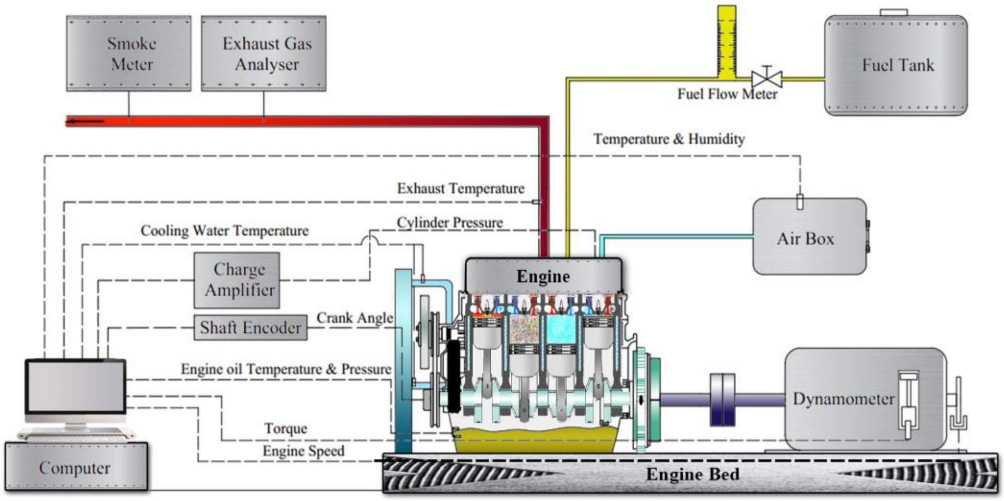

Figure 1. Schematic diagram of the experimental installation

III. RESULTS AND DISCUSSION

A. Engine Performance

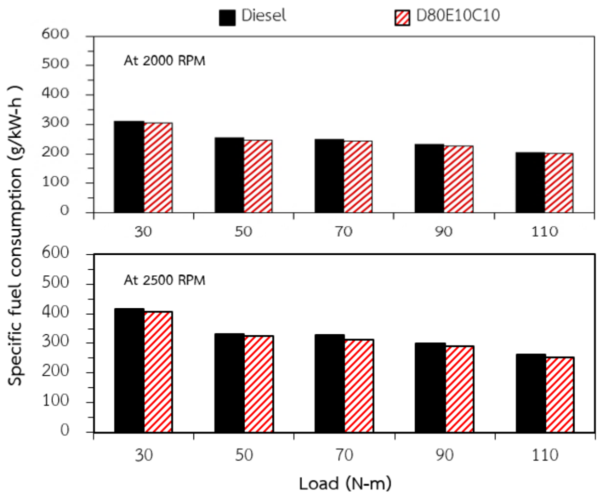

Figure 2. Brake specific fuel consumption

Fig. 2 shows the brake specific fuel consumption (bsfc) of engine under the test. It can be seen that the bsfc decreases as the engine operating loads increase. The higher engine speed results in the higher bsfc. The lower bsfc implies that less amount of fuel is needed to generate unit power output. The incorporation of castor oil-ethanol blend shows the improvement of brake specific fuel consumption at all engine operating loads tested (Fig. 2). Although, some poor properties of the ternary blend such as lower calorific value (more fuel needed to produce same power) and higher viscosity (higher surface tension affecting poor fuel atomisation) tend to increase bsfc with respect to diesel fuel, the better lubricating properties of castor oil can play a role to reduce the power lost by friction leading to the lower bsfc found in case of the castor oil blend. This positive factor to bsfc may have more effect when the engine is operated at high loads due to more fuel containing castor oil will be injected to the combustion chamber [17]. The brake thermal efficiency which is inversely proportional to bsfc is shown in Fig. 3. The lower bsfc obtained from the triblend fuel results in the higher thermal efficiency compared to diesel fuel for all engine loads tested

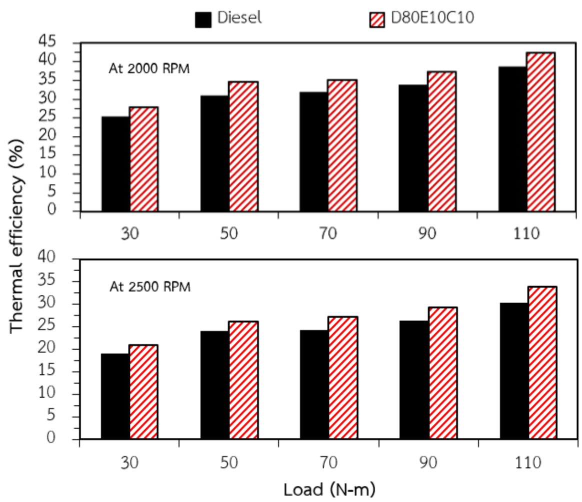

Figure 3. Engine thermal efficiency

B. Combustion Characteristics

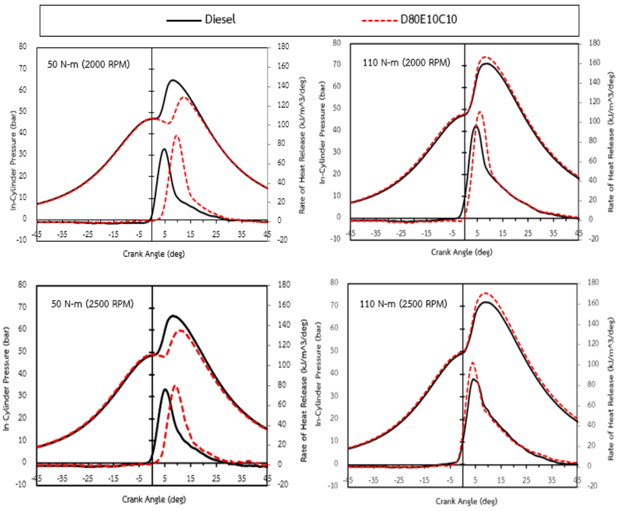

Figure 4. In-cylinder pressure and heat release rate

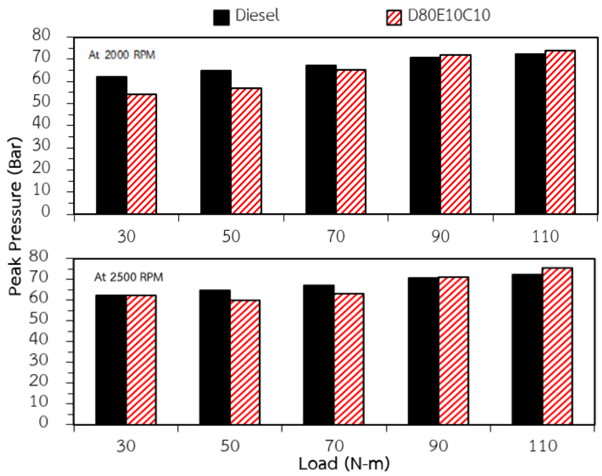

Figure 5. Peak of in-cylinder pressure

In-cylinder pressure and rate of heat release (ROHR) at 50 N.m and 110 N.m which is represented to mid and high engine operating loads for both engine speeds tested are shown in Fig. 4. The heat release rate was calculated through the first law of thermodynamics and isentropic relations, which was described in our previous work [18]. The peak of in-cylinder pressure increases as the engine load increases for both engine speeds. The combustion of more fuel which is needed to generate more power output at higher engine loads can be used to justify the increase in peak pressure inside the combustion chamber (Fig. 5). The addition of castor oil to ethanol-diesel blend tends to retard in the start of combustion (increase in ignition delay) with respect to diesel fuel. This can be attributed to the lower cetane index of castor oil and ethanol [16]. Consequently, the higher proportion of premixed combustion than in the case of diesel fuel due to the longer ignition delay of the blended fuel is observed. With longer ignition delay, there is a higher volume of premixed mixture ready to combust when combustion starts. The ignition delay due to the combustion of ternary blend decreases as the engine load increases. The similar start of combustion with diesel fuel is found with the use of the ternary blend at high engine loads (110 N.m) and the higher peak pressure in the combustion chamber is obtained. The presence of oxygen in both ethanol and castor oil which may assist the combustion process can be the reason for the higher peak of in-cylinder pressure than that of diesel fuel.

C. Engine-out Emissions

Unburnt Hydrocarbon (UHC) or Total Hydrocarbon (THC) emissions is a parameter to evaluate the combustion efficiency. More hydrocarbon emissions more incomplete combustion. The increase in engine operating loads can reduce THC emissions (Fig. 6). The higher thermal efficiency when the engine is operated at higher engine loads (Fig. 3) can be used to justify such reduction in THC emissions. The delay in the start of combustion with using the castor oil-ethanol blend leads to the increase in THC emissions compared to diesel fuel due to less available time for complete combustion to oxidise hydrocarbons. In addition, the high heat of vaporisation of ethanol can be a factor to promote the THC emissions. As ethanol was vaporised, the combustion chamber was cooled down weakening the combustion process, especially at low engine load conditions [19]. Also, the high viscosity of castor oil with high surface tension can affect the poor atomisation resulting in the high THC emissions. Although, oxygen present in both castor oil and ethanol can participate in the more complete and cleaner combustion leading to the reduction in THC emissions the effect of late start of combustion, high heat vaporisation and high viscosity seems to overcome the presence of oxygen in the ternary blend. As a consequence, the higher THC emissions can be obtained from the combustion of the ternary blend with respect to diesel fuel.

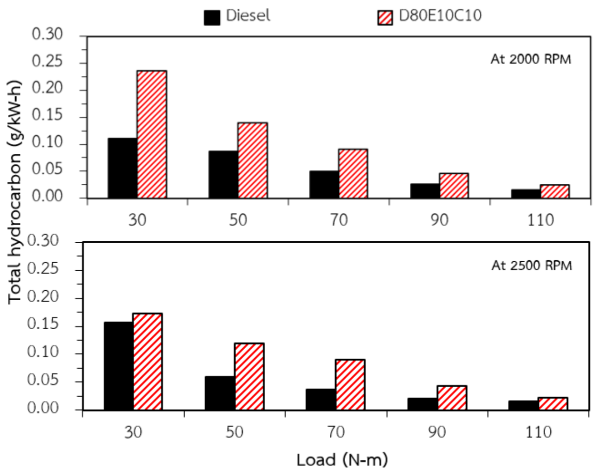

Figure 6. Unburnt hydrocarbon emissions

Another parameter used to evaluate the combustion performance is CO emissions. The increase in CO emissions implies the more incomplete combustion occurred. The higher combustion efficiency at higher engine loads leads to the decrease in CO emissions for both fuels tested (Fig. 7). In contrast to THC emissions for the high engine loads tested, the incorporation of castor oil and ethanol as blend component in diesel fuel shows the lower CO emissions compared to diesel fuel. This is likely to a consequence of the lower C/H ratio of the ternary blend by the replacement of diesel fuel with ethanol. It is suggested that this effect compensates for the potential increase in CO emissions due to the high heat of vaporization and the retard in start of combustion obtained by the ternary blend [4].

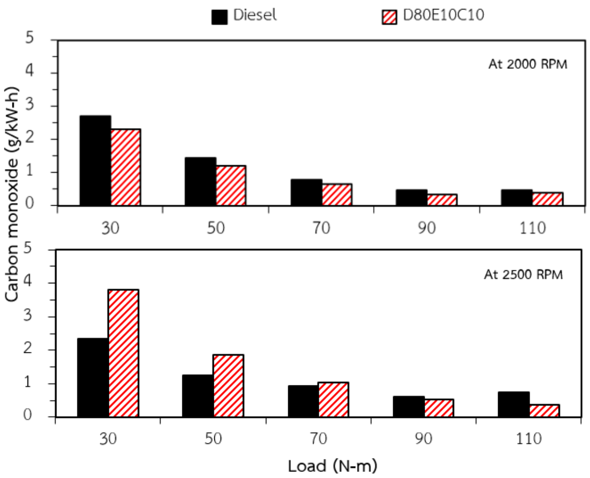

Figure 7. Carbon monoxide emissions

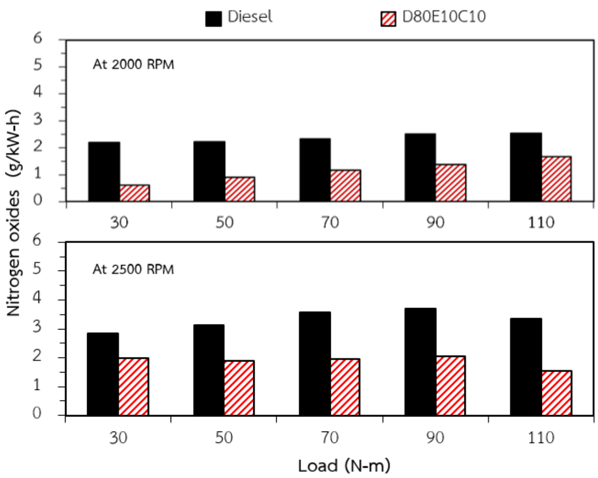

Figure 8. Nitrogen oxide emissions

Usually, the formation of NOx emissions is highly dependent on the in-cylinder pressure and the peak of heat release rate belonging to the premixed combustion phase. It is clear that the increase in NOx emissions is found with increasing the engine loads. This is mainly due to more fuels needed for producing higher power outputs at higher engine loads leading to the higher combustion temperature which help to promote the NOx formation (Fig. 8). There are some factors affecting the NOx formation and can be used to support the trend of NOx emissions by the combustion of the ternary blend. The oxygen present in fuel molecules can improve the combustion process resulting in the increase in the combustion temperature and the retard in start of combustion due to low cetane number can promote the high peak of premixed combustion, which is more favourable the NOx formation. Conversely, the reduction in NOx emissions can be obtained from combustion of fuels with high heat of vaporisation because more heat can be absorbed during the mixing process with the air, resulting in the low combustion temperature. In case of the ternary blend which is used to operate the engine under the test conditions, the higher heat of vaporization of ethanol is prominent to reduce the NOx formation. Consequently, the lower NOx emissions of the ternary blend than that of diesel fuel can be obtained. In addition, the higher viscosity of the ternary blend than diesel fuel can cause the difficulty of fuel atomization which may reduce the charge temperature and is effective to NOx mitigation [20].

The smoke emissions obtained by the combustion of diesel fuel and ternary blend is shown in Fig. 9. The increase in smoke emissions with increasing the engine operating loads for both engine speeds tested is found. This is attributed to the high overall equivalence ratio and the number of fuel rich regions in the combustion chamber when the engine is operated at high load, resulting in the high critical conditions for soot formation which relates to the increase in smoke emissions [15]. The addition of castor oil and ethanol in diesel fuel tends to decrease the smoke emissions at all conditions tested. This reduction is likely to be a consequence of the presence of oxygen in fuel molecules of both castor oil and ethanol. It has been previously reported that the hydroxyl group which belongs to both castor oil and ethanol in this study can improve the suppression of soot formation [21], [22]. In addition, the incorporating ethanol into the fuel blend reduces carbon content which decreases the possibility of soot formation.

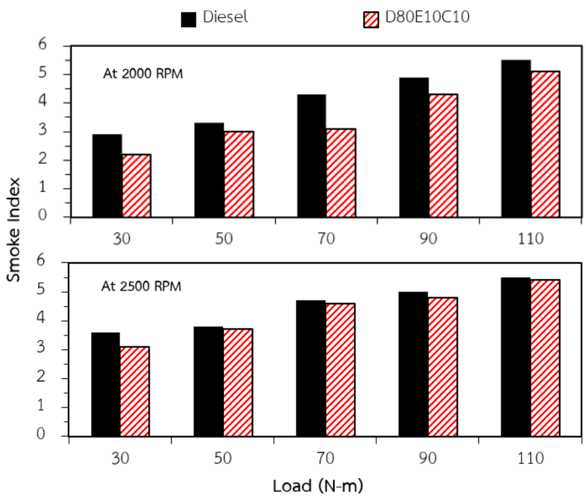

Figure 9. Smoke emissions

IV. Conclusions

The incorporation of castor oil and ethanol as blend components to reduce the use of diesel fuel in a compression ignition engine was investigated in this study. The following conclusions can be drawn.

- The high viscosity, density, flash point of castor oil can compensate the substantial reduction of such properties of ethanol leading to keep the fuel properties of the ternary blend under the limit of diesel fuel specifications.

- The better lubricating properties of the ternary blend due to castor oil can participate in the less friction loss of moving engine components, resulting in the lower brake specific fuel consumption and higher thermal of efficiency with respect to diesel fuel.
- The lower cetane index of the ternary blend tends to extend the start of combustion with respect to diesel fuel but the difference is smaller when the engine is operated at high engine loads.
- The retard in start of combustion, poor atomisation and high heat of vaporisation with ethanol blend can be used to justify the higher THC emissions from the combustion of the ternary blend with respect to diesel fuel combustion, especially at low engine loads.
- The low C/H ration with ethanol blend and the presence of oxygen in fuel molecules can be used to explain the reduction in CO emissions from the use of the ternary blend.
- The clear benefits of NOx emissions was found with the combustion of the ternary blend at all conditions tested, as a consequence of the high heat of vaporisation of ethanol.
- The presence of oxygen and the effective of hydroxyl group belonging to castor oil and ethanol to inhibit the soot formation can be reasons to support the lower smoke emissions by the ternary blend compared to diesel fuel.

The conclusions of the experimental results mentioned above indicates that the combination of castor oil and ethanol in fuel blend shows the synergistic effect in the improvement of engine-out emissions and can be a feasible alternative for next generation fuels.

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