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Plant Oil/Fusel Oil Blends as Alternative Fuels in Low- and Medium Speed Diesel Engines

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Abstract

Fuel blending is one of the methods of lowering plant oil's viscosity, which is the major parameter that leads to serious problems on diesel engine performance in terms of operation and durability. A study was carried out on fuel properties of Jatropha (JO) and Croton (CROT) seed oils blended with a distillery by-product, fusel oil (FO) (modifier) of between 20% and 50% (v/v) at room temperature (30 ± 3˚C). The effect of FO composition in the resulting blend on the kinematic viscosity and fuel combustion properties of the blends was analysed. The results were compared to the properties of crude plant oils (POs) and diesel fuel (grade-4D) specifications. The blends were found to be compatible over a wide range of compositions and exhibited much lower viscosity and better combustion properties than crude plant oil (PO) samples. The optimum proportions for a blend's viscosity to meet the specifications for diesel fuel (grade 4-D) were found to depend on the modifier characteristics; and that 20% (v/v) FO was enough to produce the desired liquid biofuel blend. The characteristics of blends presented in this work matches well with the characteristics of fuels for low- and medium-speed diesel engines. This implies that the PO/FO blends can be used as alternative fuels in low- and medium speed diesel engines.

Keywords

Fuel Oil, Jatropha Oil, Croton Oil, Plant Oil, Blending, Diesel Engines

1. Introduction

Over 2 billion people in the world - almost 40% of the world's population lives in rural [1]. However, worldwide 1.3 billion people, with an estimated 620 million people in sub-Saharan Africa do not have access to electricity while few having it, supply is often insufficient, unreliable and costly and few operating on diesel-based mini grids suffer from high costs and availability of fuel [1]-[3]. This implies that majority of rural population in the world lack electricity, of which nearly 97% live in sub-Saharan Africa and developing Asia. Lack of access to modern energy services or inadequate energy infrastructure to power their socio-economic activities, particularly for agriculture, water supply and food processing is one of the reasons for poverty domination in rural [1], [4], [5].

Millions of low- and medium speed diesel engines or PO compatible engines like Lister engines exist throughout the developing world, particularly in rural areas and which do not necessarily require high quality fuels [3], [6]. They are capable of utilising lower grade (slower burning) fuels than high speed engines and are commonly used in rural areas for socio-economic activities. These are like farm tractors, fishing boats and stationary diesel engines like cereal milling machines and electric power generators [6]-[9]. However, these engines' operation is affected by high costs and availability of fuel in these remote contexts [3], [6]. This results to inadequate mechanical power from small, slow and medium speed diesel engines and has negative impacts on socio-economic development of rural population relying on agricultural activities; as agricultural productivity is low and there is no value addition through processing.

Liquid biofuels particularly locally grown non-edible plant oils (POs) have potential of providing the energy that rural populations require as they can be easily processed and distributed to be accessed and utilised at village level for running diesel engines. However, the relatively high viscosity of POs is the major parameter that leads to serious problems on diesel engine performance in terms of operation and durability [3], [7], [10]-[15]. Moreover, majority of approaches suggested and used to modify POs in order to try to adapt the fuel (PO) to the engine, either they fall short of meeting the acceptable performance or they are not targeting in meeting rural's energy self-sufficiency. This is because the focus has been on producing high quality fuels for running in high speed diesel engines like in automobiles, trucks and cars, which are mostly found in urban areas for transport purposes and not for small, slow and medium speed diesel engines, which are common in rural areas.

Blending and mixing of various fuel components is a dilution modification technique. The viscosity of POs can also be lowered and other plant oil's characteristics improved by blending with No. 2 diesel fuel, or a solvent or an alcohol such as methanol or ethanol [14], [15], [16]-[24]. However, the unexpected results such as incompatibility during mixing can be one of the disadvantages of this approach due to dissimilarities in chemical structure and elemental contents of the components of various origins in blends [25]-[27]. Incompatibility of fuels can lead to phase separation and cause serious engine operational problems and durability. Due to this phenomenon, various studies have reported the use of coupling or blending agents to stabilise the blends [25], [27]. Reference [25] used an industrial by-product- *fusel oil* as a blending agent to ethanol/gasoline fuels and found that, fusel oil was highly effective in reducing the phase separation temperatures and increasing the water tolerance of the azeotropic ethanol/unleaded gasoline blends. 20% ethanol/gasoline blends containing 0.1% fusel oil (with 0.1%v/v water) was found to be safe to use throughout the year without any phase separation problem. Reference [17] studied the effects of plant oil-1-butanol-diesel blends on fuel properties and found that the blends exhibit similarities with diesel in the fuel characteristics. There is no reported work on the use of fusel oil in blending with plant oils. In this work, diesel (Grade 2-D) and fusel oil were used to lower the viscosity of plant oil as well as improve other fuel properties by blending.

Fusel oil is a light to dark brown liquid, with a mild choking odour; mixture of volatile, oily liquids. It is a by-product of the distillation of ethanol from the fermentation of molasses and contains mainly C3-C5 alcohols [28], [29]. Typical fusel oil composition is as shown in Table 1. On one hand, blending plant oil with fusel oil is found to be more economically appealing and environmentally sound because it makes use of by-products. Also fuel can be prepared in-situ in a simple and time saving process while recovering 100% of the plant oil as fuel. On the other hand, the advantage of using fusel oil over alcohols in blending lies in the compatibility as well as stability of the resulting blends even when there is a trace amount of water in either plant oil or fusel oil itself due to the presence of 1-butanol which acts as a surfactant that is adsorbed at oil/water interface to form monomolecular film to reduce the interfacial tension. The presence of water therefore, makes the blends appear as 'microemulsions', hence stable [30].

This study focuses on blending, as a method of improving fuel properties of plant oil to meet the specifications for diesel fuel used in low- and medium speed diesel engines or in PO compatible engines such as Lister engines, without modifying an engine. The study was part of research works by Policy Innovation Systems for Clean Energy Security (PISCES) research project.

2. Materials and Methods

2.1. Materials

Jatropha (*Jatropha curcas L.*) (JO) and croton (*Croton megalocarpus*) (CROT) seed oils were used in this study and were supplied by Diligent Tanzania Limited, while diesel (Grade 2-D or normal diesel) (D2) was bought from a local Petrol filling station (Dar es Salaam, Tanzania) and fusel oil (FO) was supplied by Illovo Sugar Limited (Durban, South Africa). D2 and FO were regarded as viscosity–modifying materials or modifiers, whereby diesel (D2) was used as a standard modifier.

Table 1. *Chemical composition of straight fusel oil (SFO) [31], [32]*

Test	Units	Specifications
Appearance	--	A light to dark brown liquid, with a mild choking odour
Density	g/cm^3 @ 25˚C	0.83-0.84
Flash Point	˚C (Closed Cup)	23-44
Test	**Units**	**Composition**
3-Methyl-1-Butanol	% w/w	44-80
2-Methyl-1-Butanol	% w/w	10-15
Isobutanol	% w/w	0-14
1-Butanol	% w/w	0-2
1-Propanol	% w/w	0-6
Ethanol	% w/w	1-17
Water	% w/w	8-21

2.2. Methodology

The blends were prepared by mixing the components (POs and modifiers) pipetted in various proportions, to lower the viscosity of POs. The modifier (FO or D2) was slowly added into an oil phase while stirring gently until the system formed a homogeneous phase. However, the order of adding the constituents to one another was not particularly critical as per [33]. All the preparations were done at room temperature (30 ± 3˚C) and did not require a big set-up and a large input of energy. Crude plant oils, modifiers and the formulated blends were tested for combustion or fuel-based properties in the Laboratories of Chemical and Mining Engineering (CME) Department, University of Dar es Salaam, Tanzania and Intertek Laboratories in Tanzania and Mombasa. The ASTM standard test methods were adopted in the analyses as shown in Table 2. The properties of the blends were compared to the properties of pure plant oil samples and diesel fuel (grade-4D) specifications (ASTM D975). Diesel fuel grade 4-D was chosen since it is slightly more viscous, used primarily in low- and medium speed diesel engines and for applications involving predominantly constant speed and load [8], [9], [34]. It was therefore considered to be close to the type of biofuel needed for use in low- and medium speed diesel engines. However, the ASTM D975 did not provide the specifications for all fuel properties. In this case, PO standards (DIN V 51605) were used instead.

3. Results and Discussion

3.1. Characterisation of Raw Material

3.1.1. Distillation Characteristics

A distillation test was carried out to show the temperature ranges over which various portions of fuel are vapourised. According to [9], characterising the fuel by the range of the boiling points of its constituents presents a more successful way of describing fuel composition. Figure 1 shows the boiling ranges of PO samples (JO and CROT), FO and D2 in the distillation curves to explain their distillation characteristics.

Results in Figure 1 indicate that JO and CROT are extremely high-boiling components while FO contains extremely low-boiling substances. This is because JO and CROT have higher densities than FO and higher-density fuels have higher boiling points [9]. Higher boiling ranges were presented by JO, CROT and fossil diesel (D2) with the distillation curve of JO lying within the boiling range of 160˚C to 385˚C, that of CROT lying in the range of 200˚C to 350˚C while the distillation curve of diesel lies within the boiling range of 180˚C to 352˚C. These boiling ranges overlap with those from literature for most diesel fuels containing hydrocarbons in which their boiling points lie within the range of 150˚C to 380˚C [8]. From [9], the boiling range of diesel is 180˚C to 340˚C. Distillation curves of all PO samples showed similar behaviour because they had almost identical boiling points. This agrees well with literature that distillation characteristics are not significantly important to plant oils as most plant oils have similar characteristics, differing mainly in fatty acid (FA) composition but most of them consist of C_{16} and C_{18} fatty acids (FAs) [11], [9].

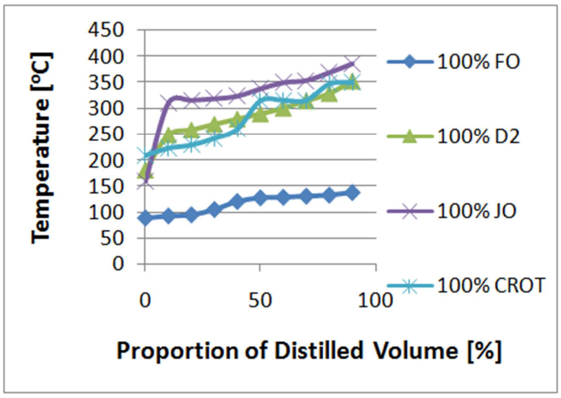

Figure 1. Comparison of Average Boiling Curves for JO, CROT, FO and D2

Distillation characteristics are linked with the fuel volatility. Volatility of the fuel influences many other properties like density, cetane number, cold-flow, flash point and viscosity. It depends on the boiling range and the content of light fractions. Increasing the contents of lower boiling fractions increases the volatility of fuels. Therefore distillation characteristics are good indicators of the presence of different compounds with high or low-boiling temperatures. Reference [25] obtained a boiling range of 80 -132˚C for FO; from Figure 1, FO presents the narrowest boiling range of 90 -138˚C. This indicates that FO is highly volatile, which implies that it contains high content of lower boiling fractions in it that makes it relatively high volatile.

The behavioural characteristics of fuels' boiling point curves have several impacts on engine operation, emissions and engine life span [11], [34]. This is due to the fact that the presence of extremely high-boiling compounds are associated with the formation of engine deposits and a gradual dilution of the lubricating oil by unburned fuel, while low- boiling compounds negatively affects the flash point.

3.1.2. Kinematic Viscosity and Other Fuel Properties

Table 2 shows properties of crude plant oils (JO and CROT), FO and diesel fuel (grade 2-D) (D2) as compared to the specifications for diesel fuel (grade-4D). It can be seen from the table that properties of crude plant oils like viscosity and flash point differ from the standard limits specified for diesel fuel (grade 4-D). Results differ with PO type as the FA composition that defines the properties of each PO differs.

Viscosity plays a major role on a long-term and trouble free engine operation [10], [12]. The viscosity of diesel fuels is important for fuel flow and engine operation such that, if the viscosity is too high results to poor atomisation of fuel spray, leading to poor combustion and loss of power and thus poor fuel economy. If the viscosity is too low, results to the lack of lubricity, which leads to injector pump wear. Also result in significant leakage of fuel from pumping elements, particularly at low pumping speeds. Viscosity reflects on the extent of intermolecular forces and is highly dependent on temperature [6], [7].

Flash point is a measure of the flammability of fuels. It is used to assess the hazard nature of the fuel particularly when considering fuel transportation and storage. Fuels with flash point below 55ºC are considered to be flammable and therefore require special costly handling to ensure human safety. While higher flash point of plant oils is considered advantageous from safety point of view [19], the same characteristic is responsible for its low volatility, which in turn is responsible for deposit formation, carbonisation of injector tips and ring sticking [14]. A combination of high viscosity and high flash point impose difficulties in engine starting, fuel ignition and fuel combustion [14], [15], [19].

Density has influence on heating value and fuel consumption, as the amount of fuel introduced into the combustion chamber is determined volumetrically. Hence, higher density means higher specific fuel consumption and vice versa [11], [35]. Cloud point (CP) provides information on the behaviour of fuels under low ambient temperatures. Solidification of fuel in cold weather may cause blockage of fuel lines and filters hence engine starting problems [11]. Water content in POs is caused by the moisture of the feedstock. Water in a fuel is undesirable because it can cause cavitation and corrosion in the injection system. It may also encourage growth of microorganisms such as bacteria and fungi, which may block the fuel filters leading to failure of the fuel supply system. Other problems associated with water content in POs include production of FFAs as water accelerates chemical reactions such as hydrolysis. FFAs can be linked with filter blockage as well. Also presence of water in the oil causes difficulties when the oil is blended with other fuels (like diesel) or solvents due to phase separation phenomenon [7], [11], [25].

In order for POs to be used as fuel in low- and medium speed diesel engines, their properties have to approximate those of fossil diesel (grade 4-D) used in low- and medium speed diesel engines or in PO compatible engines. Table 2 shows that most PO' properties are within the standard limits set for low- and medium speed diesel engines or in PO compatible engines. As per Table 2, the major problem is the viscosity.

In this study reduction of viscosity involved blending POs with a low-molecular weight or less viscous solvent regarded as modifier. Table 2 shows the properties of these modifiers. The modifiers used were having lower values of kinematic viscosity and density as well as good cold temperature characteristics as seen in Table 2. Mixing of PO with SFO (water content: 8-21% v/v) (from Table 1), phase separation occurred, forming non-homogenous blends. However, dried FO with characteristics shown in Table 2 formed clear, transparent homogenous (or continuous phase) formulations.

Table 2. *Characteristics of Pure Samples*

Property	ASTM Test	JO	CROT	FO	Diesel (Grade 2-D) (D2)	PO standards (Europe) (DIN V 51605)[7]	Specifications for Diesel Fuel (Grade 4-D) [9]
Kinematic Viscosity [mm^2/s] @ 40°C	D2196 (Test Method A)	37.78	30.94	2.44	4.91	36 (max.)	5.5 - 24
Density [g/cm^3] @ 15°C	D1298	0.920	0.922	0.840	0.835	0.90-0.93	--
Flash Point [°C]	D93	282	285	41	90	220 (min.)	55 (min.)
Calorific Value [MJ/kg]	D4868	44.4	44.37	42.29	45.77	36 (min.)	--
Cloud Point [°C]	D2500	-3	-18	-26	-3	--	6 (max.)
Water Content [% volume]	D95	<0.05	<0.05	1.65	0.00	0.075(max.)	0.50 (max.)

3.2. Characterisation of Blends

3.2.1. Distillation Characteristics

The distillation curves of blended samples (Figures 2 and 3) are compared to those of PO samples (JO and CROT), FO and D2 in Figure 1 to explain their distillation characteristics. The maximum limited temperature when 90% (v/v) is recovered (T_{90}) is set at 360˚C for fossil diesel and plant derived fuels like fatty acid methyl esters (FAME) [11]. The T_{90} is believed to be linked with the crankcase oil dilution. Therefore higher T_{90} values are undesirable since they increase the chances that some fuel will escape combustion and leak past the piston rings to the crankcase [9]. In this case, all the T_{90} values for blends in Figures 2 and 3 were within the allowable limit.

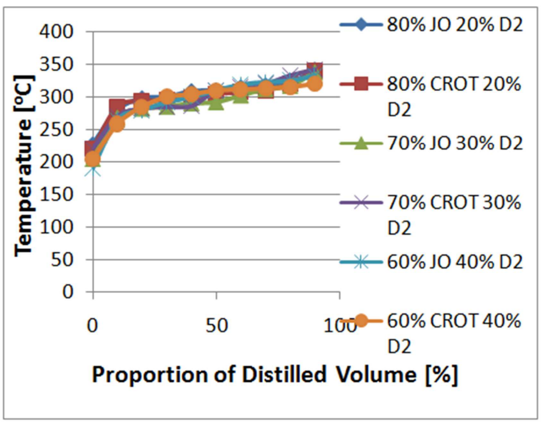

Figure 2. *Comparison of Average Boiling Curves for JO/D2 and CROT/D2 Blends*

Distillation characteristics were relevant to the blends since they constitute components with different boiling temperatures like in fossil diesel fuels. Higher boiling ranges were presented by JO/D2 and CROT/D2 blends (Figure 2) with the distillation curves lying within the boiling range of 190˚C to 350˚C. The resulting blends with FO component like JO/FO, JO/FO/D2, or CROT/FO, CROT/FO/D2 blends in Figure 3 have improved boiling range characteristics and improved volatilities since JO and CROT are extremely high-boiling components while FO contains extremely low-boiling substances as per Figure 1.

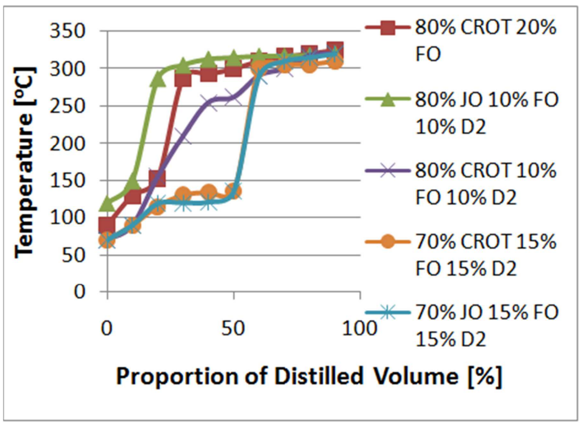

Figure 3. *Average Boiling Curves for JO/FO/D2 and CROT/FO/D2 Blends*

According to [8], the contents of heavier components in fuel oils used for low- and medium-speed diesel engines are higher than those in automotive diesel fuels for high-speed diesel engines. Therefore fuel oils for low- and medium-speed diesel engines have higher boiling ranges consisting of higher distillate fractions with higher boiling components than those of automotive diesel fuels for high-speed diesel engines. This is because low- and medium-speed diesel engines can tolerate lower grade fuels. Distillation characteristics of blends presented in this study matches well with the distillation characteristics of fuels for low- and medium-speed diesel engines.

Observations in almost all three figures (Figures 1 to 3) displaying distillation characteristics show that at the initial stages of distillation, the boiling temperature markedly rises due to the removal of low-boiling substances, and then the distillation continues at almost constant temperatures.

3.2.2. Kinematic Viscosity

Figures 4 and 5 present the effect of modifiers on the trend of kinematic viscosity of POs. The trends show that kinematic viscosity of POs decreases as the % PO decreases (and vice versa) in various formulations. Also they show that FO has greater effect than D2 in cutting down the viscosity of POs as the PO/FO trends are steeper than those of D2. Similarly, JO/D2 and CROT/D2 blends showed slightly higher viscosities than JO/FO and CROT/FO blends of same proportions. This is due to the relatively higher viscosity of D2 than the viscosity of FO (Table 2). All the blends display relatively low values as compared to the crude PO samples (100% JO, 100% CROT). The values are also below the maximum limit (24 mm^2/s) specified for diesel fuel (grade 4-D). This implies that almost all the blends can also run on low- and medium speed diesel engines.

From these trends (Figures 4 and 5), it can be seen that the amount of modifier to be added and for a blend's viscosity to meet the specifications for diesel fuel (grade 4-D), depend on the modifier characteristics.

3.2.3. Flash Point

Table 3 show the flash point of different blends. The results in Table 3 were compared with the values of 100% FO, 100% D2 and crude PO (100% JO, 100% CROT) samples in Table 2 as well as with the minimum specified standard limit of diesel fuel (grade 4-D), which is 55˚C. It can be seen that there is remarkable improvement of flash point in the formulated blends since the flash point of the blends are much lower than those of PO samples in Table 2.

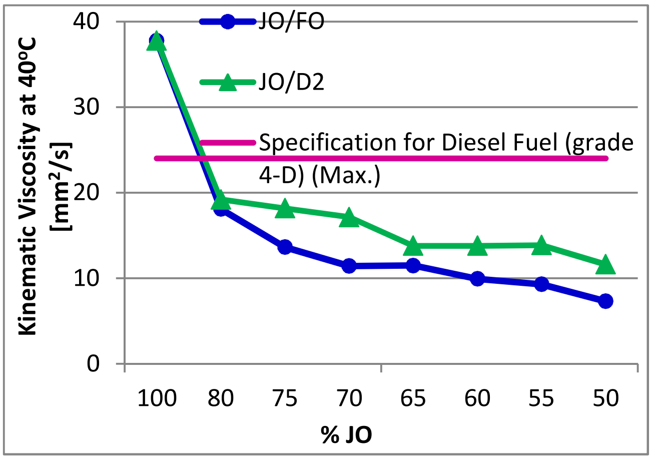

Figure 4. *Kinematic Viscosity Trends of JO/FO and JO/D2 Blends*

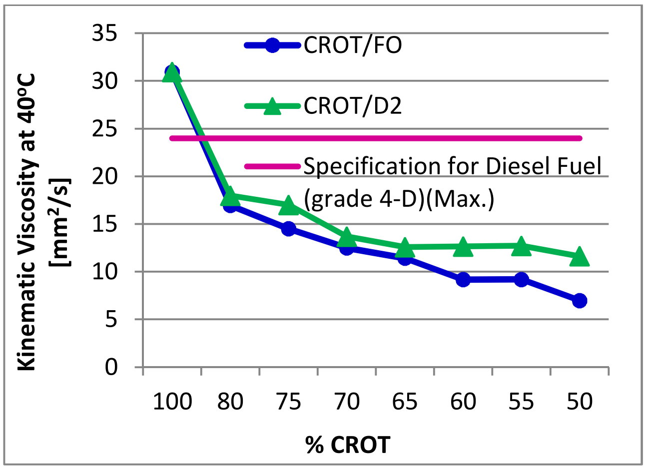

Figure 5. *Kinematic Viscosity Trends of CROT/FO and CROT/D2 Blends*

Table 3. *Flash Point for Different Blends*

Tested Sample	Flash Point [˚C]	Tested Sample	Flash Point [˚C]
80% JO 20% FO	56	80% CROT 20% FO	75
70% JO 30% FO	55	70% CROT 30% FO	64
60% JO 40% FO	52	60% CROT 40% FO	55
80% JO 10% FO 10% D2	62	80% JO 20% D2	130
70% JO 15% FO 15% D2	58	70% JO 30% D2	118
60% JO 20% FO 20% D2	55	60% JO 40% D2	104
80% CROT 10% FO 10% D2	77	60% CROT 40% D2	106
70% CROT 15% FO 15% D2	65		
Limit Value (Requirements) (Min.)	55 [Diesel Fuel Grade 4-D Specifications (ASTM D975)]		

The effect of FO in improving the flash point and hence volatilities of JO and CROT was very significant such that only about 20% of FO was enough to bring down the flash point of CROT from 285°C (Table 2) to 75°C (80% CROT/20% FO blend) (Table 3), which is about 75% improvement while that of JO after blending was 56°C (80% JO/20% FO blend). However, when 20% FO was replaced by 20% diesel in 80%JO/20% FO blend, flash point rises to 130°C from 56°C. Likewise, the flash point of 80% CROT/10% FO/10% diesel blend is 77°C, slightly higher than that of 80% CROT /20%

FO blend (Table 3). This is because FO has lower flash point temperatures than D2 (Table 2), which is influenced by its high volatility as indicated in Subsection 3.1.1. This implies that a small amount of FO is needed for improving the volatility of PO sample as compared to D2. However, it can be seen that the introduction of D2 in blends containing higher FO percent (v/v) helped to improve the volatility and consequently, the flash point of blends.

3.2.4. Heating Values (Calorific Values)

The calculated values of heat of combustion or gross calorific values or higher heating values (HHV) of JO and CROT blends are as shown in Table 4. The HHV values were found to decrease as the % (v/v) FO increases and (vice versa); and increases as the % (v/v) D2 increases. However, all the values were found to be above the minimum standard limit of 36 MJ/kg according to PO standards (DIN V 51605), which is an advantage in terms of engine performance. FO and FO-blends displayed relatively lower HHV than that of D2 due to high alcohol content in the FO samples (Table 1) as indicated by [14] on the effect of alcohol content in microemulsions on volumetric heating values. The difference between PO, D2 and FO in heating values can be due to their difference in chemical composition. On one hand, PO contains a substantial amount of oxygen in its molecules. Similar observation is found in FO modifier composition. On the other hand, D2 is composed of mainly saturated hydrocarbons (75%), primarily the paraffins [11], [34]. They are therefore virtually oxygen-free compounds. The presence of chemically bound oxygen or intrinsic oxygen in a fuel sample has significant influence on the heating values and fuel consumption [11]. Oxygen decreases the heat of combustion of the fuel. However, the intrinsic oxygen content in a fuel sample may have positive impact to the environment as it influences the stochiometric air-fuel ratio during the combustion process, which ensures complete combustion, in turn will help reduce gaseous and particulate exhaust emissions.

Table 4. *Calorific Values for Different Blends*

Tested Sample	Calorific Value (HHV) [MJ/kg]	Tested Sample	Calorific Value (HHV) [MJ/kg]
80% JO 20% FO	43.99	80% CROT 20% FO	43.92
70% JO 30% FO	43.80	70% CROT 30% FO	43.64
60% JO 40% FO	43.42	60% CROT 40% FO	43.41
80% JO 20% D2	44.72	80% CROT 20% D2	44.66
70% JO 30% D2	44.88	70% CROT 30% D2	44.80
60% JO 40% D2	44.98	60% CROT 40% D2	44.93
80% JO 10% FO 10% D2	44.31	80% CROT 10% FO 10% D2	44.56
70% JO 15% FO 15% D2	44.08	70% CROT 15% FO 15% D2	44.88
60% JO 20% FO 20% D2	44.16	60% CROT 20% FO 20% D2	44.11
Limit Value (Requirements) (Min.)	36 [PO standards (DIN V 1605)]		

4. Conclusion

This study shows that viscosity of jatropha and croton oils can be lowered by blending with fusel oil; and that the PO/ FO blends are compatible over a wide range of compositions and exhibit much lower viscosity and better combustion properties than crude PO samples. The characteristics of blends presented in this work matches well with the characteristics of fuels for low- and medium-speed diesel engines. Overall results show that the kinematic viscosity of the blend is highest when the mixture contains little or no diesel and slightly FO and much PO. The optimum proportions for a blend's viscosity to meet the specifications for diesel fuel (grade 4-D), depend on the modifier characteristics. The results show that 20% (v/v) FO is enough to produce a liquid biofuel blend that can operate in low- and medium speed diesel engines as well as safe fuel to work with. This implies that the PO/FO blends can be used as alternative fuels in low- and medium speed diesel engines.

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