American Journal of Engineering, Technology and Society
2015; 2(3): 35-45
Published online April 20, 2015 (http://www.openscienceonline.com/journal/ajets)

Plant Oil Blends as Alternative Fuels for Low- and Medium Speed Diesel Engines: Natural Gas Condensate Utilisation

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To cite this article

Happiness Mlay, Jamidu H. Y. Katima, Rwaichi J. A. Minja. Plant Oil Blends as Alternative Fuels for Low- and Medium Speed Diesel Engines: Natural Gas Condensate Utilisation. *American Journal of Engineering, Technology and Society*. Vol. 2, No. 3, 2015, pp. 35-45.

Abstract

The high viscosity of pure plant oils (POs) reduces the feasibility of using plant oils as diesel engine fuel as reported by various researchers. However, the significant impact of this parameter depends on the kind of engine. Fuel blending is one of the methods of lowering viscosity. A study was carried out on fuel properties of Jatropha (JO) and Croton (CROT) seed oils blended with a by-product of Songosongo natural gas extraction - natural gas condensate (NGC) (modifier) of between 5% and 50% (v/v) at room temperature (30 ± 3˚C). Mixture design was used to analyse the effect of NGC composition in the resulting blend on the kinematic viscosity and fuel combustion properties of the blends. The results were also compared to the properties of crude POs and diesel fuel (grade 4-D) 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 parameters for formulating blends were found to depend on the modifier characteristics and that 10% (v/v) NGC was enough to produce the desired liquid biofuel blend. The characteristics of blends presented in this work meet the specifications for diesel fuel (grade 4-D) and so matches well with the characteristics of fuels for low- and medium-speed diesel engines. This implies that the PO/NGC blends may be potential alternative fuels in low- and medium speed diesel engines, which are common engines found in rural areas and so PO/NGC blends fuels may contribute in meeting rural's energy self-sufficiency while at the same time making utilisation of natural gas condensate.

Keywords

Natural Gas Condensate, Jatropha Oil, Croton Oil, Plant Oil, Blending, Low- and Medium Speed Diesel Engines

1. Introduction

Energy adequate has a close link to poverty reduction, economic growth and sustainable development [1]. This is well recognised by various global fora, like the United Nations (UN) Sustainable Energy for All Initiative in 2011, which seeks to deliver access to modern energy for all by 2030. Also the Millennium Summit (September, 2000) in New York, where the largest gathering of the world (189 nations) in history adopted the UN Millennium Declaration, commonly referred to as the Millennium Development Goals (MDGs) and agreed to be achieved by the year 2015. All these initiatives had the aim of achieving, among other things, promoting energy access to poor communities. However, to date, the progress achieved in providing accessible and affordable, clean and sustainable energy services in rural areas (particularly in sub-Saharan Africa), is poor. An estimated 620 million people in sub-Saharan Africa (two thirds of the population in sub-Saharan Africa) do not have access to electricity while few having it, supply is often insufficient, unreliable and costly [2]-[4]. 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 worldwide [1], [2], [5].

In Tanzania, despite many efforts, 36 million people (about 76% of the country population), majority being rural residents have no access to electricity and lack basic household energy needs: lighting, cooking and heating [2]. This has led to a disparity in wealth between rural and urban and has also led to poor health care delivery and undermined economic development through agriculture and industrial production [2], [6]. Access to energy services is therefore prerequisite for development. Greater levels of access to modern energy services are required, particularly in rural areas to spearhead economic growth in the rural, and agriculture mechanisation is one of the means of promoting that [7].

Liquid biofuels have potential of being alternative fuels that can provide the affordable access to energy that rural populations require for poverty reduction and sustainable development. They are produced from biomass and present proper utilisation of bioenergy that can provide a clean, cost-effective, sustainable and accessible fuel needed to power the rural agro-processing activities from small, slow and medium speed diesel engines in order to bring socio-economic development for rural community [7], [8]. The interest in liquid biofuels is growing rapidly worldwide today due to the recent fossil fuels' crises; price fluctuations and uncertainties concerning their availability since they are non-renewable, hence not sustainable as well as environmental problems associated with their uses due to emission of greenhouse gases (GHGs) from fossil fuel combustion [9]-[13]. The use of diesel lead to generation of GHG emission amounting to 2.67 kg of CO_2 per litre of diesel used [14].

The use of locally grown non-edible plant oils (POs) has potential of providing a low cost, sustainable solution. Historically, the idea of using plant oil (PO) as diesel fuel substitute is not new; it started as early as 1900s. Reference [15] used pure palm oil to fuel a stationary diesel engine for the energy supply of small village in the Amazon basin. Reference [16] reported the use of pure Jatropha oil in a stationary diesel engine (generator) for electrification in rural area, Southern part of Tanzania. Tanzania Traditional Energy Development Organisation (TATEDO) in Tanzania has been involved in the development of liquid biofuels since 2003 and efforts have been directed in supporting the small scale farmers to grow and use Jatropha oil for provision of modern energy services and the organisation used Lister engines in their various projects fuelled with diesel or biodiesel or Jatropha oil [1], [4], [17]. Also Reference [5] presents a number of case studies in developing countries of established initiatives using PO as fuel in running diesel engines.

However, findings from all these studies and tests done on using pure POs as fuel in unmodified diesel engines have shown that there are problems on the engine performance in terms of operation and durability associated with direct use of POs as diesel fuels [10]-[13]. These problems are highly influenced by the chemical composition of POs, which differs from that of fossil fuels; leading to different physical and chemical properties as compared to fossil fuels [10], [15], [18]. The main difference between PO and fossil fuels is the oxygen content. POs have oxygen content ranging from 10% to 45% (w/w) while fossil diesel fuel is oxygen-free [8], [10], [12]. POs contain C_{16} to C_{18} FAs with 1-3 double bonds per molecule whereas fossil diesel fuel consists of about 30-35% aromatic hydrocarbons, 65-70% paraffins and traces of olefins mostly in the range of C_{10} to C_{16} [10]. Therefore POs have almost three or more times higher molecular weight than diesel fuel [12] and more chemically reactive than diesel fuel due to high degree of unsaturation of POs. The presence of oxygen and the high molecular weight have impacts on some properties of POs such as viscosity and heating values [10], [12].

Due to these problems, several techniques have been suggested and used to modify POs in order to try to adapt the fuel (PO) to the engine [10], [12], [13]. However, the focus of majority of these techniques have been on producing high quality fuels for high speed diesel engines like in automobiles, trucks and cars, which are often found in urban areas and not on quality of fuels for low- and medium speed diesel engines like in farm tractors, fishing boats and stationary diesel engines like cereal milling machines and electric power generators, which are commonly utilised at village level for various socio-economic activities and which do not necessarily require high quality fuels [4], [7], [18]-[22]. Their ruggedness, robust design makes them tolerant to fuel quality [4], [5], [7], [18], [21].

Low- and medium speed diesel engines are the common engines found in rural in food processing, power generation, agriculture and transportation applications [7]. In Tanzania for example, by 2013 the number of tractors and power tillers was 9,148 and 5,520 respectively, as reported in the Tanzania national assembly [23] by the Minister of Agriculture Food Security and Cooperatives (Hon. Christopher Chiza), which most likely are being utilised for farming in rural setting. Also according to [4] and [7], the Lister engine types, which are examples of low- and medium speed diesel engines are used throughout the developing countries, mostly in rural areas for agro-processing activities. Currently, these engines operate on fossil fuels and very small percentage on electrical energy, implying that the mechanisation of agriculture, which is the main occupation in rural society strongly depends on fossil fuels as per [24]. However, their operation suffers from high costs and availability of electrical energy and fossil fuels in rural remote contexts [4], [7], [25]. It is possible to modify PO into liquid biofuel just to meet the specifications for low- and medium speed diesel engines [26], [27] and reduce competition with higher quality fuels thereby stabilising fuel price.

Blending and microemulsions can be used in lowering the viscosity as well as changing other plant oil's characteristics. Various tests on blending have reported that the viscosity of POs can be lowered by blending with diesel fuel (grade 2-D) or a solvent or an alcohol such as methanol or ethanol and the blends exhibit similarities with diesel in the fuel characteristics [12], [13], [26]-[34]. The properties of the final fuel composition are determined by the relative proportions of the components involved, selection of PO and the surfactant [33], [35].

In most of these investigations, POs formed the continuous fuel phase and their properties indicate the possibility to apply them as alternative fuels. Also it has been found that since modifying POs to be used as a fuel does not necessarily require maintaining it in an edible form; non-edible solvents (or blending agents) and fluids of any nature like by-products can be used provided that they are compatible with POs.

Therefore according to [36], various methods and experiments can be conducted to determine the kind of additives or modifiers, which can be added to overcome the negative characteristics of POs. Different modifiers other than diesel and alcohols are yet to be tested. In this work, the viscosity of plant oil and other fuel properties were improved by blending with a by-product of natural gas extraction, natural gas condensate.

Table 1. *Chemical Composition of Songosongo Natural Gas Condensate [37]*

Component	Chemical Formula	Molar Composition [%]	Concentration [g/l]
Propane	C_3H_8	0.126	0.113
Butane	C_4H_{10}	0.670	0.601
Pentane	C_5H_{12}	1.262	1.133
Hexane	C_6H_{14}	2.183	1.959
Heptane	C_7H_{16}	24.738	22.147
Octane	C_8H_{18}	33.883	30.368
Nonane	C_9H_{20}	37.264	33.361

Natural Gas Condensate (NGC) is a mixture of heavier hydrocarbons, mainly octane, nonane and heptane that condense out to a liquid at normal pressure and temperature, which is recovered from the natural gas. The condensate which is recovered from gas stream at Songosongo Island (South-Eastern part of Tanzania) has been found to have limited utilisation and hence it has generally been treated as waste [37], [38]. This calls for a need to find NGC utilisation and this study has found its utilisation in PO blending. Blending PO with NGC is found to be more economically and environmentally sound because it makes use of by-products and promotes the concept of utilising wastes as valuable raw material. Also fuel can be prepared in-situ in a simple and time saving process while recovering 100% of the plant oil as fuel, unlike other PO modifying techniques like Transesterification in biodiesel production, which end up with more than 10% glycerol as a byproduct [10], [12].The composition of the Songosongo natural gas condensate was as shown in Table 1 as per [37].

This study focuses on blending, as a method of improving fuel properties of plant oil in order to try to adapt the fuel (PO) to the diesel engine of low- and medium speed. 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

Non-edible oils from jatropha (*Jatropha curcas L.*) (JO) and croton (*Croton megalocarpus*) (CROT) seeds were used in this study and were supplied by Diligent Tanzania Limited. These oils are very promising raw materials for local energy and fuel production because of their high oil content. The most abundant fatty acids (FAs) in Jatropha and Croton oils are oleic acid and linoleic acid and the two oils are classified as unsaturated oils containing high percentage of unsaturated FAs in a range of 73-87% [39]-[50]. Viscosity–modifying materials or modifiers were petroleum diesel (grade 2-D or normal diesel) (D2) of commercial grade – as standard modifier and natural gas condensate (NGC), which is a by-product of Songosongo natural gas extraction. Diesel (grade 2-D) (D2) was bought from a local Petrol filling station (Dar es Salaam, Tanzania) while Natural Gas Condensate (NGC) was supplied by Tanzania Petroleum Development Corporation (TPDC) (Dar es Salaam, Tanzania).

Table 2. *Mixture Design for Plant Oil and NGC Blends*

Component	Name	Lower (v/v)	Upper (v/v)
PO	Plant Oil	50	95
NGC	Natural Gas Condensate	5	50

Table 3. *Design Table for Plant Oil and NGC Blends (Randomised)*

Run	Type	PO	NGC
1	1	50.0	50.0
2	-1	61.3	38.8
3	1	95.0	5.0
4	-1	83.8	16.3
5	0	72.5	27.5

Table 4. *Mixture Design for Plant Oil, NGC and Diesel Blends*

Component	Name	Lower (v/v)	Upper (v/v)
PO	Plant Oil	50	90
NGC	Natural Gas Condensate	5	25
Diesel	Diesel	5	25

Table 5. *Design Table for Plant Oil, NGC and Diesel Blends (Randomised)*

Run	Type	PO	NGC	Diesel
1	-1	80	10	10
2	2	80	15	5
3	-1	70	10	20
4	0	70	15	15
5	2	60	15	25
6	1	70	25	5
7	-1	70	20	10
8	1	90	5	5
9	-1	60	20	20
10	2	60	25	15
11	1	50	25	25
12	1	70	5	25
13	2	80	5	15

2.2. Methodology

2.2.1. Preparation of Blends

The blends were prepared by mixing the components (POs and modifiers) pipetted in various proportions. The modifier (NGC 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 [51]. 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.

2.2.2. Design of Experiments (DoE)

The experimental design was *Mixture Design*, using *Minitab* Statistical Package (*Version 15*). The main response was the blend's viscosity. The response, which is the quality or performance of the product based on the blend's viscosity was a function of the relative proportions of the oil and modifiers, where the quantities of components, measured in volumes added up to a common total of 100 ml for total mixture amount for single amount. The response was analysed using Mixture Design equations which were modelled on experimental results where it was decided that quadratic polynomial equation will sufficiently model the response surface, so a second-degree design was created [52] (Minitab, V 15). The lower bound and upper bound to model the mixture design were set as shown in Tables 2 and 4 and generated randomised design Tables 3 and 5 for conducting experiments. Factors like temperature, pressure, mixing time and speed were kept constant throughout.

2.2.3. Regression Analysis

The resultant regression for mixtures was determined and regression coefficients were computed and used for the estimation of the effects. The response surface model (a polynomial equation) was fitted to the data using multiple regressions (by Minitab V 15). To model the mixture data for 3-variable case, the response of tested mixed component proportions was used for prediction using a quadratic polynomial equation (Equation 1) (a 3-variable case) [52], [53].

$$y = b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (1)$$

Where:

y stands for the dependent variable values (the predicted response);

b_1, b_2, b_3 stands for the regression coefficients (linear coefficients);

b_{12}, b_{13}, b_{23} stands for the interaction coefficients;

x_1, x_2, x_3 are the coded variables or components.

To model the mixture data for 2-variable case, the response of tested mixed component proportions was used for prediction using a quadratic polynomial equation (Equation 2) (a 2-variable case) [52], [53].

$$y = b_1x_1 + b_2x_2 + b_{12}x_1x_2 \qquad (2)$$

Where:

y stands for the dependent variable values (the predicted response);

b_1, b_2 stands for the regression coefficients (linear coefficients);

b_{12} stands for the interaction coefficients;

x_1, x_2 are the coded variables or components.

The mean viscosity reduction in various blends with different proportions were analysed and tested statistically using ANOVA. The confidence interval of 90% ($\alpha = 0.1$), *one-tailed test* of the parameters was used for a check of each regression. p-value for each coefficient tested the null hypothesis that the coefficient is equal to zero (no effect). Therefore low p-values (p-values $\leq \alpha = 0.1$) suggested the predictor is a meaningful addition to the model (indication that the null hypothesis is false) [52], [54]. One-tailed test hypothesis was used since the interest was one-sided test that uses a null hypothesis, H_O stating that:

$$H_O : \mu_{current} = \mu_{prev}$$

Or an alternate hypothesis, H_A stating that:

$$H_A : \mu_{current} < \mu_{prev}$$

to see if the blend's mean viscosity ($\mu_{current}$) is lower than the crude PO's mean viscosity (μ_{prev}) in observing the effect of modifier in lowering the viscosity of PO.

2.2.4. Tests and Analyses

The blends were allowed to settle for about 1 h prior to analyses. The ASTM standard test methods were adopted in the analyses as shown in Table 6. 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 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 [19], [20], [55]. 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 as shown in Table 6.

3. Results and Discussion

3.1. Characterisation of Raw Material

3.1.1. Distillation Characteristics

Fuel volatility can be characterised by the flash point and the distillation curve. Distillation characteristics are the limits of the respective proportions of condensates recovered by atmospheric distillation of fuel samples at specified temperatures, used to determine distillation curve. Distillation curve is characterised by the initial point, which is the temperature of the fuel when the first drop of liquid leaves the condenser, the temperatures when each 10% of the liquid is removed and the end point, which is the temperature for the last drop of fuel collected [20]. According to [20], characterising the fuel by the range of the boiling points of its constituents presents a more successful way of describing fuel composition. Therefore a distillation test was carried out to show the temperature ranges over which various portions of fuel are vapourised. Figure 1 shows the boiling ranges of PO samples (JO and CROT), NGC and D2 in the distillation curves to explain their distillation characteristics.

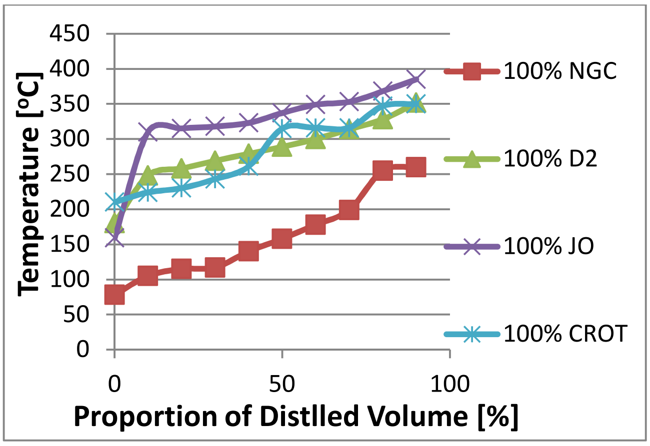

Figure 1. Comparison of Average Boiling Curves for JO, CROT, NGC and D2

Distillation characteristics are good indicators of the presence of different compounds with high or low-boiling temperatures and are considered as important quality parameters in fossil diesel fuels which are more complex mixtures of aliphatic and aromatic hydrocarbons with far different boiling points. Results in Figure 1 indicate that JO and CROT are extremely high-boiling components while NGC contains extremely low-boiling substances. This is because JO and CROT have higher densities than NGC and higher-density fuels have higher boiling points [20]. 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 D2 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 [19]. From literature, the boiling range of D2 is around 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} FAs [10], [20].

Distillation characteristics have several impacts on engine operation, emissions and engine life span. This is due to the fact that distillation characteristics are linked with the fuel volatility, which 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. From Figure 1, NGC presents the narrowest boiling range of 78-260˚C. This indicates that NGC is highly volatile, which implies that it contains high content of lower boiling fractions in it that makes it relatively high volatile. 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 and other fuel properties. Distillation characteristics are also significant due to the fact that the distillation curve enables to obtain values for the 10% distillation point (T_{10}), 50% distillation point (T_{50}) and 90% distillation point (T_{90}) to meet fuel specifications and to calculate the cetane index (from the 50% distillation temperature), which is very close to cetane number [10], [20].

Table 6. Characteristics of Pure Samples

Property	ASTM Test	JO	CROT	NGC	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] @ 40ºC	D2196 (Test Method A)	37.78	30.94	1.27	4.91	36 (max.)	5.5 - 24
Density [g/cm^3] @ 15ºC	D1298	0.920	0.922	0.800	0.835	0.90 - 0.93	--
Flash Point [ºC]	D93	282	285	33	90	220 (min.)	55 (min.)
Calorific Value [MJ/kg]	D4868	44.4	44.37	46.21	45.77	36 (min.)	--
Cloud Point [ºC]	D2500	-3	-18	-27	-3	--	6 (max.)
Water Content [% volume]	D95	<0.05	<0.05	0.00	0.00	0.075 (max.)	0.50 (max.)
Sulphur [% mass]	D4294	0.003	0.004	0.011	0.032	10 (max.)	2 (max.)

3.1.2. Kinematic Viscosity and Other Fuel Properties

Table 6 shows properties of crude plant oils (JO and CROT), NGC 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 deviate from the standard limits specified for diesel fuel (grade 4-D). However, most JO' properties do not differ from CROT' properties because the two oils are both classified as unsaturated oils (as per Section 2.1). Table 6 shows that most PO' properties are within the standard limits set for low- and medium speed diesel engines. As per Table 6, the major problem is the viscosity. Viscosity plays a major role on a long-term and trouble free engine operation [12], [15], [56]. To approximate PO's viscosity to that of fossil diesel used for low- and medium speed diesel engines (diesel fuel - grade 4-D), this study performed blending of POs with NGC, which has high volatility, lower values of kinematic viscosity and density as well as good cold temperature characteristics and zero water content as seen in Table 6.

3.2. Characterisation of Blends

3.2.1. Distillation Characteristics

The distillation curves of blended samples (Figures 2 to 4) are compared to those of PO samples (JO and CROT), NGC 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) [10]. 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 [20]. In this case, all the T_{90} values for blends in Figures 2 to 4 were within the allowable limit.

Although distillation characteristics are of minor relevance to POs, as most POs have almost identical boiling points, they were relevant to the blends since they constitute components with different boiling temperatures like in fossil diesel fuels. Higher boiling ranges were presented by PO/D2 blends (Figures 2 and 3) with the distillation curves lying within the boiling range of 190˚C to 350˚C.

Figures 2 to 4 indicate the resulting blends with NGC component like JO/NGC, JO/NGC/D2, or CROT/NGC, CROT/NGC/D2 blends having improved boiling range characteristics and improved volatilities since JO and CROT are extremely high-boiling components while NGC contains extremely low-boiling substances as per Figure 1.

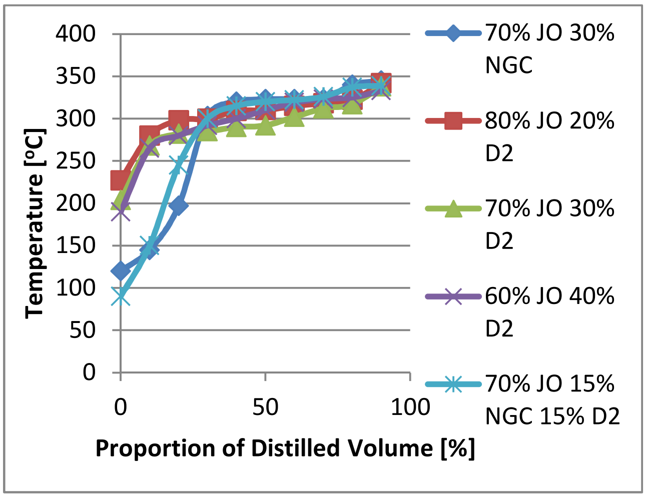

Figure 2. *Comparison of Average Boiling Curves for Various JO Blends*

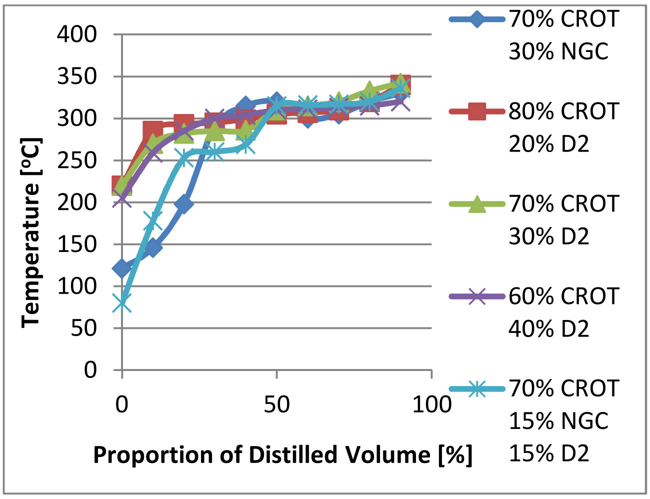

Figure 3. *Average Boiling Curves for Various CROT Blends*

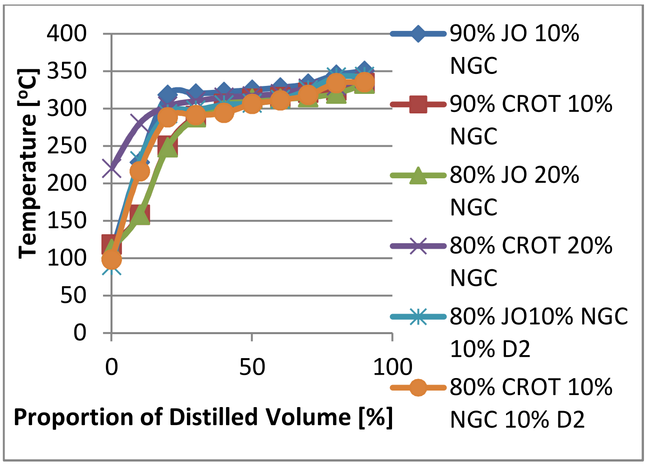

Figure 4. *Average Boiling Curves for Various PO/NGC and PO/NGC/D2 Blends*

According to [19], 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 [4], [7], [18]-[22]. Distillation characteristics of blends presented in this study (Figures 2 to 4) matches well with the distillation characteristics of fuels for low- and medium-speed diesel engines. Observations in all the four figures (Figures 1 to 4) 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. The idea of introducing diesel was significant for the volatility and flash point values of the blends.

3.2.2. Kinematic Viscosity

Figures 5 and 6 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. The values are also below the maximum limit (24 mm^2/s) specified for diesel fuel (grade 4-D). It can be seen from these trends that only 10% (v/v) NGC was enough to produce a liquid biofuel blend' viscosity that meet the specifications for diesel fuel (grade 4-D). It is about 22.9 mm^2/s for a 90% JO/10% NGC blend (Figure 5) and about 17.9 mm^2/s for a 90% CROT/10% NGC blend (Figure 6).

From Figures 5 and 6, the two POs (JO and CROT) show almost similar trends. It was expected that since most plant oils in spite of having similar characteristics, they differ in FA composition, therefore the trends might differ. However, in this case, the two oils (JO and CROT) have identical FA composition and are both classified as unsaturated oils (as per Section 2.1) and so the trends and the amount of modifier to be added for a blend's viscosity to meet the specifications for diesel fuel (grade 4-D) were only influenced by the modifier characteristics.

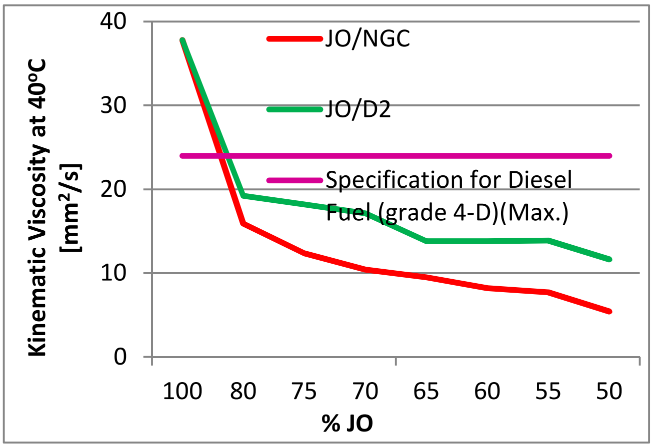

Figure 5. Kinematic Viscosity Trends of JO/NGC and JO/D2 Blends

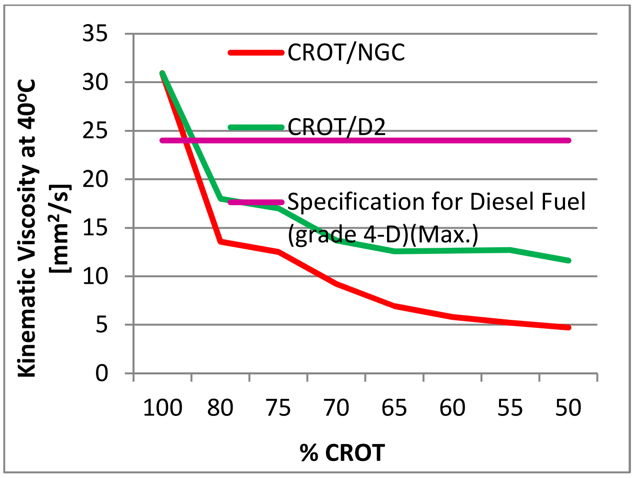

Figure 6. Kinematic Viscosity Trends of CROT/NGC and CROT/D2 Blends

3.3. Statistical Modelling Results

This section presents statistical modelling of the effects of various component proportions on the kinematic viscosity. Regression analyses results indicated correlation between the simulated (fit) and the observed (actual) values for kinematic viscosity.

Table 7. Response for Plant Oil and NGC Mixture Design and Predicted Viscosity

StdOrder	RunOrder	PtType	Blocks	Factors		Responses	
				PO	NGC	Kinematic Viscosity [mm²/s]	
				x_1	x_2	V Actual	V' Fit
1	1	1	1	50	50	6.2	6.5
4	2	-1	1	61.3	38.8	8.5	7.7
2	3	1	1	95	5	27.9	27.8
5	4	-1	1	83.8	16.3	18.3	18.3
3	5	0	1	72.5	27.5	11.0	11.6

Table 7 presents results of response and predicted kinematic viscosity for PO and NGC mixture design. Regression results were as shown in simplified Tables 8 and 9.

Table 8. Estimated Regression Coefficients for Viscosity for Plant Oil and NGC Mixture Design (Component Proportions)

Term	Coef	SE Coef	T	P	VIF
PO	32.9	1.062	*	*	5.306
NGC	35.2	8.242	*	*	58.53
PO*NGC	-110.1	16.162	-6.81	0.021	79.981

S = 0.765353, PRESS = 12.1877, R-Sq = 99.62%, R-Sq (pred) = 96.09%, R-Sq (adj) = 99.25%

Equation 3 is the model for PO and NGC mixture.

Regression equation for PO and NGC blend:

$$v = 32.9x_1 + 35.2x_2 + (-110.1)x_1x_2 \quad (3)$$

Where: x_1, x_2 are the codes for PO and NGC respectively.

The variability of the model is $R^2 = 99.62\%$, showing that the model can be used, with good accuracy, to predict the behaviour of the selected response [57].

Kinematic viscosity was calculated by using Equation 3. The regression results showed that together, the two components account for 99.62% of the variance of blend's viscosity and that the two-blend mixture of PO by NGC ($t = -6.81$; $p = 0.021$) for *PO and NGC mixture design* (Tables 8) might be judged as significant as p-value was less than α (α = 0.1), indication that the null hypothesis is false.

Table 9. Analysis of Variance (ANOVA) for Viscosity for Plant Oil and NGC Mixture Design (Component Proportions)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	310.319	310.3190	155.1595	264.88	0.004
Linear	1	283.13	0.0516	0.0516	0.09	0.795
Quadratic	1	27.189	27.1886	27.1886	46.42	0.021
Residual Error	2	1.172	1.1720	0.5858		
Total	4	311.491				

Equation 4 is the model for PO and D2 mixture. Kinematic viscosity was calculated by using Equation 4. The regression results showed that together, the two components account for 98.88% of the variance of blend's viscosity.

Regression equation for plant oil and diesel blend:

$$v = 24.886x_1 + 3.100x_2 + (-9.877)(x_1 * x_2) \quad (4)$$

Where: x_1, x_2 are the codes for PO and D2 respectively.

The variability of the model is $R^2 = 98.88\%$. An R^2 value which is very close to 1 indicates that the model can be used to predict the variability in the response with good accuracy.

The results of response and predicted kinematic viscosity for PO, NGC and D2 mixture design are presented in Table 10. Regression results were as shown in simplified Tables 11 and 12.

Table 10. *Response for Plant Oil, NGC and Diesel (D2) Mixture Design and Predicted Viscosity*

StdOrder	RunOrder	PtType	Blocks	Factors			Responses	
				PO	NGC	D2	Kinematic Viscosity [mm²/s]	
				x_1	x_2	x_3	V Actual	V' Fit
1	1	1	1	90	5	5	28.1	27.7
2	2	1	1	80	5	15	21.5	21.6
3	3	1	1	80	10	10	20.4	20.0
4	4	1	1	80	15	5	17.8	18.7
5	5	1	1	70	5	25	16.6	17.1
6	6	1	1	70	10	20	15.9	15.6
7	7	1	1	70	15	15	13.8	14.3
8	8	1	1	70	20	10	13.2	13.2
9	9	1	1	70	25	5	12.9	12.4
10	10	1	1	60	15	25	12.4	11.5
11	11	1	1	60	20	20	10.5	10.5
12	12	1	1	60	25	15	9.8	9.7
13	13	1	1	50	25	25	8.3	8.7

Kinematic viscosity was calculated by using Equation 5.
Regression equation for PO, NGC and D2 blend:

$$\nu = 37.4x_1 + 46.4x_2 + 35.9x_3 + (-134.8)(x_1 * x_2) + (-86.3)(x_1 * x_3) + (-47.9)(x_2 * x_3) \quad (5)$$

Where: x_1, x_2, x_3 are the codes for PO, NGC and D2 respectively.

The regression results showed that together, the three components account for 99.17% of the variance of blend's viscosity and that PO by NGC (t = -3.18; p = 0.015) and PO by D2 (t = -2.04; p = 0.081) mixtures for *PO, NGC and D2 mixture design* (Table 11) were the only two-blend mixtures that might be judged as significant. The variability of the model is $R^2 = 99.17\%$, showing that the model can be used, with good accuracy, to predict the behaviour of the selected response [57].

Contour and Surface Plots are useful for establishing desirable response values and mixture blends. A contour plot provides a two-dimensional view where all points that have the same response are connected to produce contour lines of constant responses. A surface plot provides a three-dimensional view that may provide a clearer picture of the response surface. A Contour (Figure 7) and a surface plot (Figure 8) base on the model represented by Equation 5. Figure 9 is a Response Trace Plot of PO/NGC/D2 blend.

A contour plot (Figure 7) shows that all points are in constraint region where the lowest kinematic viscosity was obtained in the middle of bottom line with points: Row 13: PO 50 NGC 25 Diesel 25. The closer to NGC, the lower the kinematic viscosity and it can also clearly visualised in a surface plot (Figure 8). However, it can be seen that only little modifier can bring the oil to the required viscosity of diesel fuel (grade-4D). It is shown in Figure 7 that all the blends display relatively low kinematic viscosity values as compared to the crude PO samples (100% PO). The values also lies within the specified range for diesel fuel (grade 4-D), which can operate on low- and medium speed diesel engines. This implies that almost all the blends can also run on low- and medium speed diesel engines. Both contour (Figure 7) and surface (Figure 8) plots showed that the kinematic viscosity of the blend was highest when the mixture contains little or no modifiers.

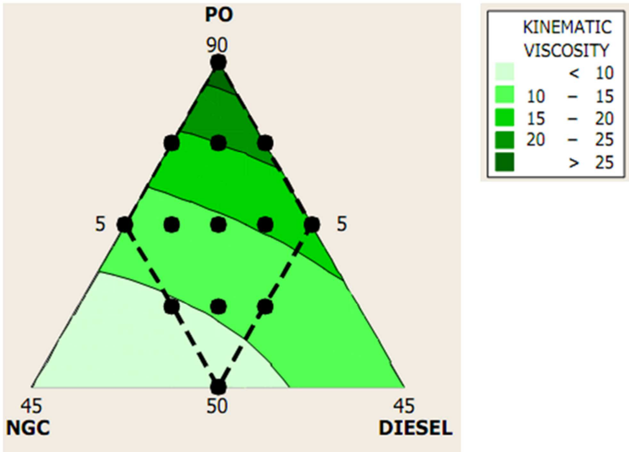

Figure 7. *Contour Plot for Plant Oil, NGC and Diesel Blend*

Table 11. *Estimated Regression Coefficients for Viscosity for Plant Oil, NGC and Diesel Mixture Design (Component Proportions)*

Term	Coef	SE Coef	T	P	VIF
PlantOil	37.4	1.290	*	*	25.32
NGC	46.4	30.561	*	*	791.75
Diesel	35.9	30.561	*	*	791.75
PlantOil*NGC	-134.8	42.320	-3.18	0.015	638.40
PlantOil*Diesel	-86.3	42.320	-2.04	0.081	638.40
NGC*Diesel	-47.9	62.402	-0.77	0.468	92.48

S = 0.653927, PRESS = 19.1431, R-Sq = 99.17%, R-Sq (pred) = 94.68%, R-Sq (adj) = 98.58%

Table 12. *Analysis of Variance (ANOVA) for Viscosity for Plant Oil, NGC and Diesel Mixture Design (Component Proportions)*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	357.135	357.1349	71.42699	167.03	0.000
Linear	2	336.917	0.0383	0.01917	0.04	0.956
Quadratic	3	20.217	20.2175	6.73916	15.76	0.002
Residual Error	7	2.993	2.9933	0.42762		
Total	12	360.128				

A Response Trace plot or component effects plot (Figure 9) shows the effect of each component on the response. A response trace plot shows that plant oils (POs) have longer response traces than those of modifiers (NGC and D2). This is because POs have larger ranges (upper bound - lower bound) while the modifiers have shorter response traces (Figure 9) meaning that they have smaller ranges. Information about the component effects from the trace response plot indicates that:

- As the proportion of plant oil
  - Increases (and the other mixture components decreases), the viscosity of the blend increases;
  - Decreases (and the other mixture components increases), the viscosity of the blend decreases;
- As the proportion of a modifier
  - Increases (and the other mixture components decreases), the viscosity of the blend decreases;
  - Decreases (and the other mixture components increases), the viscosity of the blend increases

Also Figure 9 shows that NGC has steeper response trace than D2. This implies that NGC has greater effect than D2 in cutting down the viscosity of Pos. The same observation is shown by Figures 5 and 6. This is due to the relatively higher viscosity of D2 than the viscosity of NGC as per Table 6.

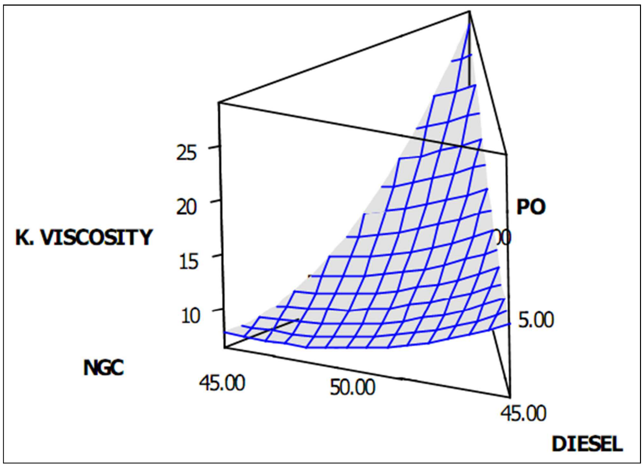

Figure 8. *Surface Plot for Plant Oil, NGC and Diesel Blend*

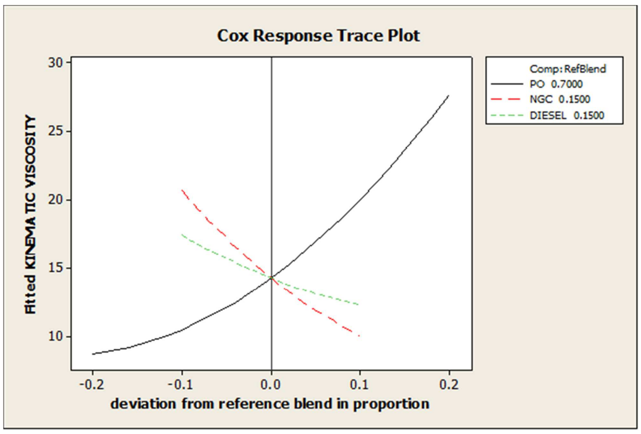

Figure 9. *Response Trace Plot of Plant Oil, NGC and Diesel Blend*

4. Conclusion

This study shows that viscosity of plant oils can be lowered by blending with natural gas condensate; and that the PO/ NGC 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 meet the specifications for diesel fuel (grade 4-D) and so 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 NGC and much PO. The optimum parameters for formulating blends in this study were found to depend on the modifier characteristics only, as the two POs (Jatropha and Croton seed oils) have identical FA composition and so the FA composition of PO had no influence. It was found that 10% (v/v) NGC was 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 most of the PO/NGC blends can be used as alternative fuels in running low- and medium speed diesel engines. Low- and medium speed diesel engines are common engines found in rural areas and since most PO/NGC blends do not meet the standards for high speed diesel engines' fuels, less competition with higher quality fuels is expected. This ensures stable price of PO/NGC blends fuels, hence contributing in meeting rural's energy self-sufficiency while at the same time making utilisation of NGC.

Acknowledgements

The Authors acknowledge the financial support provided by the PISCES research project, which was a five-year initiative project funded by the UK's Department for International Development (DFID). PISCES which had partners in Kenya, India, Sri Lanka, United Kingdom and Tanzania was intended to provide policymakers with information and approaches that they can apply to unlock the potential of bioenergy to improve energy access and livelihoods in poor communities. The Authors also acknowledge the Department of Chemical and Mining Engineering, University of Dar es Salaam for their co-support in this work as well as Tanzania Petroleum Development Corporation (TPDC) for supplying the natural gas condensate.

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