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Full Length Research Paper

Investigation of the relationship between some basic flow properties of shea butter biodiesel and their blends with diesel fuel

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In this study, the density, viscosity, cloud and pour points of shea butter biodiesel-diesel fuel blends were measured following ASTM test methods. In order to predict these properties, mixing rule was evaluated as a function of the volume fraction of biodiesel in the blend. The effects of biodiesel fraction on each of these properties in addition to the effects of temperature on density and viscosity were investigated. The blends (B2, B5, B10, B20, B50 and B75) were prepared on a volume basis. Generalized equations and Arrhenius equation for predicting the density and viscosity of the blends were used. The low values of the absolute average deviations (AAD) and the maximum absolute deviations (MAD) obtained confirmed the suitability of the mixing rule used. For all the blends, it was observed that the results from the measured and estimated values of density and viscosities were in good agreement. From the results, the density and viscosities of the blends decreased with increase in temperature while these properties increased with increase of biodiesel content in the fuel blend. The cloud point and the pour point of the blend increased as the biodiesel concentration increases. The values obtained from empirical equations for predicting the relationship between cloud point, pour point and biodiesel content in the blends were in good agreement with the experiments.

Key words: Shea butter biodiesel, blend, diesel, flow properties.

INTRODUCTION

The possibility of using vegetable oils as fuel has been recognized since the beginning of diesel engines. Vegetable oil has very high viscosity for use in most existing diesel engines as a straight replacement fuel oil. There are a number of ways to reduce the viscosity of vegetable oils. One of the most common methods used to reduce oil viscosity is called transesterification. This process results in the production of a fuel comprised of mono-alkyl esters of long chain fatty acids called biodiesel. Biodiesel is the most widely accepted alternative fuel for diesel engines due to its technical, environmental and strategic advantages. It is the first alternative fuel that passed the US EPA-required Tier I and Tier II Health Effects testing requirements of the Clean Air Act Amendments of 1990 (Yuan et al., 2004).

Biodiesel has enhanced biodegradability, reduced toxicity and improved lubricity in comparison with

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conventional diesel fuels. In addition, it is completely miscible with petroleum diesel, allowing the blending of these two fuels in any proportion (Benjumea et al., 2008). Biodiesel is a promising alternative to crude oil-derived diesel fuels because it is renewable, significantly reduces particulate matter, hydrocarbon, carbon monoxide and life cycle net carbon dioxide emissions from combustion sources [Yuan et al., 2009]. In addition, it has the potential to relieve the non-crude oil-producing countries from their dependence on foreign crude oil.

Edible and non-edible vegetable oils remain the major feedstock for biodiesel production. Tallow or animal fats, used cooking oil and algae have also been used [Enweremadu and Mbarawa, 2009].

When using biodiesel in unmodified diesel engines, one issue that needs to be addressed is that biodiesel fuels have different properties from petroleum diesel. Biodiesel, produced from vegetable oil or animal fats, generally has higher density, higher viscosity, higher cloud point and higher cetane number, and lower volatility and heating value compared to commercial grades of diesel fuel [Öner and Altun, 2009]. Other drawbacks of biodiesel include worse low temperature properties, greater emissions of some oxygenated hydrocarbons, higher specific fuel consumption and decrease in brake thermal efficiency [Sudhir et al., 2007; Rao et al., 2008]. Engine manufacturers have raised concerns about some of these properties as they may affect the engine performance and emissions since the engines were originally optimized with petroleum diesel [Yuan et al., 2004]. The fuel properties of biodiesel must meet ASTM D-6751 and EN 14214 specifications in USA and Europe. Although B100 (100 vol. % biodiesel) is rarely used, when these limits are met, the biodiesel can be used in most modern engines without any modifications while maintaining the engine's durability and reliability [Van Gerpen, 2005]. Although biodiesel is miscible with petroleum diesel in any proportion, not all the blend proportions may be used in diesel engines. The Engine Manufacturers Association (EMA) reported that biodiesel blends up to 5% should not cause engine and fuel system problems (EMA, 2003). Blends of up to 20% biodiesel mixed with petroleum diesel fuels can be used in nearly all diesel equipment and are compatible with most storage and distribution equipment. Hence the warranty on most new engines only allows a maximum of B20 (20 vol. % biodiesel and 80 vol. % petroleum diesel) to be used [Petersen, 2008]. It is asserted that 90% of air toxics can be eliminated by using B100 whereas 20 to 40% are reduced using B20 [USDOE, 2004]. However, if the full benefits of biodiesel as a renewable fuel are to be realized, it must be used in a greater proportion. Therefore, to further tap into the benefits of using biodiesel, there is the need to increase ratio of biodiesel in biodiesel-diesel blends.

It is important to know the basic properties of biodiesel-diesel blends as some of these properties are required as input data for predictive and diagnostic engine combustion models. In addition, it is necessary to know if the fuel resulting from the blending process meets the standard specifications for diesel fuels [Benjumea et al., 2008]. Density and kinematic viscosity are the parameters required by biodiesel and diesel fuel standards because they are key fuel properties for diesel engines [Alptekin and Canakci, 2008]. Density directly affects the engine performance characteristics, and it is used as a precursor for a number of other fuel properties such as heating value and viscosity [Yuan et al., 2009]. On the other hand, diesel fuel injection systems measure the fuel by volume. So the changes in the fuel density will influence engine output power due to a different mass of fuel injected [Alptekin and Canakci, 2008]. Even more than density, kinematic viscosity is an important property regarding fuel atomization, as well as fuel distribution. High viscosity causes poor fuel atomization during the spray, increases the engine deposits, needs more energy to pump the fuel and wears fuel pump elements and injectors [Kinast, 2003].

The density and viscosity of the fuels affect the start of injection, the injection pressure, and the fuels spray characteristics, so that they influence the engine performance, combustion and exhaust emissions. Analysis of these results can easily be carried out when the key fuel properties of biodiesel-diesel fuel blends are known.

As the fuel properties of biodiesel differ from those of diesel fuels, the different engine performance and emissions will occur when biodiesel is used in diesel engines. Therefore, more investigations are needed about the fuel properties of biodiesels and their blends with diesel fuels before using them in a diesel engine. Various techniques or methods and empirical model have been developed for measuring and predicting the density and viscosity of pure biodiesel and its blends with diesel [Tat and Van Gerpen, 1999; Yuan et al., 2005; Allen et al., 1999; Krisnangkura et al., 2006; Tate et al., 2006a, b].

The cloud and pour points of biodiesel can be decreased by blending it with No. 2 diesel fuel as the cloud and pour points of biodiesel are higher than petroleum diesel. Also, the lubricity of petroleum diesel increases on addition to biodiesel [Demirbas, 2005]. Various techniques and empirical models have been developed for cloud and pour points measurements of pure biodiesel from different feed stocks and its blends with diesel fuels [Mirante and Coutinho, 2001; Coutinho et al., 2002]. Both cloud and pour points of biodiesel and its blends with diesel fuel decreases with biodiesel concentration [Joshi and Pegg, 2007] and by the addition of pour point depressants [Huang and Wilson, 2000; Kerschbaum and Rinke, 2004].

The objectives of this study are to investigate the relationships between some of the basic flow properties of shea butter biodiesel and their blends with diesel fuel as a function of biodiesel fraction and temperature.

Table 1. Basic properties of shea butter biodiesel and diesel fuel.

Properties	Shea butter biodiesel	Diesel
Density at 15°C (kg/m^3)	877	854
Kinematic viscosity at 40°C (mm^2/s)	4.42	2.87
Flash point (°C)	171	55
Pour point (°C)	3	-15
Cloud point (°C)	6	-13
High heating value (MJ/kg)	37.93	45.27
Cetane number	58	50
Acid value (mg KOH/g)	0.28	0.5
Ester content (%)	95.21	-

MATERIALS AND METHODS

Biodiesel production and blend preparation

The shea butter biodiesel used in this study was produced by Enweremadu and Alamu [2010]. The biodiesel is made from shea butter by modifying a two-stage acid-base transesterification process found online. The biodiesel conforms to the ASTM D6751 standard. During the acid-catalysed stage, the amount of methanol used is 20% of the volume of oil plus 60% excess methanol. One litre of crude shea butter and 40% of the required volume of methanol was measured and added to the heated shea butter at 55°C. The mixture was stirred gently for 5 min using a magnetic stirrer until it became murky. 1 ml of 95% sulfuric acid was added to the mixture. Holding the temperature at 55°C, the mixture was stirred gently for 1 h at 500 to 600 rpm. The heat was removed and stirring continued for another hour after which the mixture was allowed to settle for 2 h. To the remaining 60% of the methanol 4.9 g potassium hydroxide (KOH) was added to form potassium methoxide solution. 50% of this solution was added to the acid treated mixture and stirred gently for 5 min and allowed to settle for 6 to 12 h after which the glycerine was drained off. During the alkali-catalysed stage, the mixture was heated to 55°C and the second half of the methoxide solution was slowly stirred in, mixing at the same speed for 1 h. On completion of the reaction, the product was poured into a separating funnel and allowed to settle for 18 to 24 h. After separation of the biodiesel and glycerol, the fatty acid methyl ester was washed with 2 ml of 10% phosphoric acid added to warm distilled water and dried with anhydrous sodium sulphate. The measured and calculated characteristics of the biodiesel are presented in Table 1.

There are three blending techniques generally used: Splash blending, in-tank blending and in-line blending [Petersen, 2008; Joshi, 2007]. Splash blending is an effective and efficient blending technique that is widely used. Due to the cloud point of the biodiesel being approximately 6°C, commercial grade No. 2 diesel was splash-blended with the biodiesel in a conical flask with continuous stirring to ensure uniform mixing. The biodiesel was blended with the diesel fuel at a volume base of 2, 5, 10, 20, 50 and 75%. The properties of No. 2 diesel fuel are listed in Table 1. Blends were prepared on a volume basis at the ambient temperature of the blending location (about 25ºC) [Benjumea et al., 2008].

Density measurement

Density bottle was used to measure the density of the shea butter biodiesel, diesel fuel and their blends. The measurements were taken at 15°C. The biodiesel and the blends were cooled and measurements taken with the density bottle when their temperatures reached 15°C. The tests were conducted three times and the average results recorded.

The measured density of biodiesel and their blends with commercial grade No. 2 diesel were correlated as the function of biodiesel fraction and temperature respectively using the linear square method. The linear regression equations formulated are as follows:

$$\rho = a(T) + b \quad (1)$$

Where T is the temperature (°C), ρ is the density (kg/m^3), a and b are correlation coefficients.

$$\rho = Ax + B \quad (2)$$

Where ρ is the density (kg/m^3), A and B are coefficients and x is biodiesel fraction.

The calculated values for the shea butter biodiesel and its blends were compared with measured values and the results are shown in Tables 2 and 3.

The density of the blends was also calculated from the densities of each component using the equation (Clements, 1996):

$$\rho_{\text{blends}} = \rho_i \ x_i \quad (3)$$

Where ρ_{blends} and ρ_i represent the density of the blends and the component i respectively, and x_i is biodiesel fraction.

This equation has been employed to calculate the densities of the blends based on the measured densities of the pure biodiesel and No. 2 diesel fuel. The results are used to determine the applicability of the blending rule to the tested biodiesel fuel according to Yuan et al. (2004).

Viscosity measurement

Kinematic viscosity was determined using Ubbelohde glass capillary kinematic viscometer in a constant temperature water bath according to the standard method. Three measurements were taken for each fuel sample and the average results recorded.

For viscosity as a function of biodiesel fraction, several studies have been carried out in which the experimental data have been

Table 2. The measured and calculated density value of shea butter biodiesel-diesel fuel blends using Equation (2).

Fuel	Measured	Calculated	A	B	R^2	Error	Absolute error (%)
B75	0.8695	0.8704				0.0010	0.10
B50	0.8645	0.8649				0.0004	0.05
B20	0.8582	0.8582	2×10^{-5}	0.8537	0.9951	0.0000	0.00
B10	0.8561	0.8560				0.0001	0.01
B5	0.8551	0.8549				0.0002	0.02
B2	0.8545	0.8542				0.0003	0.04

Table 3. The measured and calculated viscosity value of shea butter biodiesel-diesel fuel blends.

Fuel	Measured	A	B	C	R^2	Calculated		Absolute error		Error (%)	
						Eq. 4	Eq. 5	Eq. 4	Eq. 5	Eq. 4	Eq. 5
B75	3.8850				0.9999	3.8851	3.8519	0.0001	0.0331	0.002	0.85
B50	3.4412					3.4465	3.4337	0.0053	0.0075	1.54	0.22
B20	3.0580	7×10^{-5}	7×10^{-3}	2.8585		3.0475	3.0621	0.0105	0.0041	0.34	0.13
B10	2.9451					2.9453	2.9516	0.0002	0.0065	0.01	0.22
B5	2.8952					2.8999	2.8883	0.0047	0.0069	0.16	0.24
B2	2.8744					2.8746	2.8815	0.0002	0.0071	0.01	0.25

correlated by empirical second-degree equation because a linear equation does not fit the data well. The same approach was used in this study.

$$\eta = Ax^2 + Bx + C \quad (4)$$

where A, B, C are coefficients.

The Grunberg-Nissan mixing rule has been widely used for predicting viscosity of liquid mixtures. The equation uses mole fraction and absolute viscosity. However, in this study the volume fraction and kinematic viscosity were used because the estimated values were close to the measured values. Therefore, the Arrhenius-type equation was used:

$$\ln \eta_B = V_{SB} .\ln \eta_{SB} + V_D .\ln \eta_D \quad (5)$$

where η_B, η_{SB}, η_D is the kinematic viscosities of the blend, shea butter oil biodiesel and diesel respectively (mm^2/s), and V_{SB}, V_D is the volume fraction of shea butter biodiesel and diesel respectively. The use of the Arrhenius-type equation has been found to be useful in predicting the viscosity of biodiesel-diesel fuel blends without needing viscosity measurements [Alptekin and Canakci, 2008]. The viscosity of the blends were calculated from Equations (4) and (5) and validated by using the measured viscosity values.

The variation of kinematic viscosity with temperature for different types of fluids is commonly represented by Andrade equation [Benjumea et al., 2008; Kerschbaum and Rinke, 2004]:

$$\eta = e^{\left(A + \frac{B}{T} + \frac{C}{T^2} \right)} \quad (6)$$

where η is the kinematic viscosity (mm^2/s), and T is temperature (°C).

Such as in density, the equations obtained from regression analysis by using the measured values, were used to estimate the dependence of viscosity of the biodiesel blends on biodiesel fraction and temperature respectively. Mixing rules were used to estimate the basic properties of blends as a function of pure fuel properties and biodiesel content. The suitability of these rules was evaluated by means of the absolute average deviation (AAD) and maximum average deviation (MAD), and calculated as;

$$AAD = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{EXP - CAL}{EXP} \right| \quad (7)$$

$$MAD = \max 100 * \left| \frac{EXP - CAL}{EXP} \right| \quad (8)$$

where N is the number of experimental points, EXP and CAL stand for experimental and calculated respectively.

Measurement of cloud and pour points

The cloud point is the temperature at which a cloud of wax crystals first appear in a liquid when it is cooled under controlled conditions during a standard test (ASTM D2500) while the pour point is the temperature at which the fuel can no longer due to gel formation (ASTM D97). The cloud and pour points were measured according to ASTM D2500 and ASTM D97 respectively, using a cloud and pour points apparatus. All the measurements were done in triplicate for each sample and the results averaged.

RESULTS AND DISCUSSION

Density and viscosity results

Many national standards on biodiesel give the density of

Table 4. Cloud point values of shea butter biodiesel-diesel fuel blends.

Fuel	Measured	Calculated	Absolute error (K)	Error (%)
B100	279	279.01	0.01	0.004
B75	275	274.87	0.13	0.047
B50	270	270.23	0.23	0.085
B20	264	264.01	0.01	0.003
B10	262	261.78	0.22	0.083
B5	261	260.64	0.36	0.137
B2	260	259.94	0.06	0.023
D	259	259.48	0.48	0.185

Table 5. Pour point values of shea butter biodiesel-diesel fuel blends.

Fuel	Measured	Calculated	Absolute error (K)	Error (%)
B100	276	275.8	0.2	0.072
B75	271	271.3	0.3	0.111
B50	266.7	266.5	0.2	0.074
B20	260.6	260.3	0.3	0.115
B10	258	258.2	0.2	0.077
B5	257	257.1	0.1	0.038
B2	256.6	256.4	0.2	0.077
D	256	256	0.0	0.000

biodiesel from 860 to 900 kg/m^3 [Meher et al., 2006]. The density of the biodiesel produced in this study lies between these values. Petroleum diesel has a lower density than biodiesels. The density and viscosity of biodiesel has been known to depend on the fatty acid composition of the mixed esters and their purity [Allen et al., 1999]. Also, the density of diesel fuel varies depending on the refinery feedstock and the blending streams in the diesel fuel boiling range. The density of the blends will lie between the values of pure biodiesel and diesel fuel.

Table 2 shows the measured density values, the calculated density values from regression analysis the regression coefficient, the absolute error and percentage error in Equation (2). The measured and the calculated values are in very good agreement. The minimum regression coefficient (R^2) is 0.9951 for the biodiesel-diesel fuel blends. The maximum absolute error between the measured and calculated density values is 0.0004.

According to some standards such as UNI 10635 (Italy) and SS 155435 (Sweden), at 40°C the viscosity of biodiesel falls between 1.9 and 6.0 mm^2/s. The viscosities of biodiesel fuels are higher than those of diesel fuels. Hence it is expected that the viscosities of the blends will fall in the range between the pure biodiesel and the diesel fuel. Table 3 shows the measured viscosity values, the calculated viscosity values from regression analysis, the regression coefficient, absolute and percentage error obtained in Equations (4) and (5), respectively. The minimum regression coefficient (R^2) is 0.9999 for the fuel blends. The maximum percentage error obtained from Equation (4) is 1.54% compared to 0.85% from Equation (5).

Cloud and pour points

Cloud and pour points are the key flow properties for winter fuel specification. The pour point is always lower than the cloud point. All biodiesel fuels exhibit poor cold flow properties with cloud and pour points higher than those of petroleum diesel fuel and the same applies to shea butter biodiesel. The results of measured, calculated values, absolute error and percentage error of the cloud and pour points of the shea butter biodiesel and its blends are presented in Tables 4 and 5, respectively.

The measurements of the cloud and pour points have been correlated as function of blend by empirical second-order polynomial equations. A regression analysis of the data was carried out using POLYMATH®. From the regression coefficient, it was observed that the regression analysis of the data shows that the polynomial equation is better fitted for the measured values than a linear equation. The proposed equation for calculating cloud point as a function of blend is

$$T_{cp} = 259.5 + 0.2347 V_B + 0.00039 V_B^2 \quad (9)$$

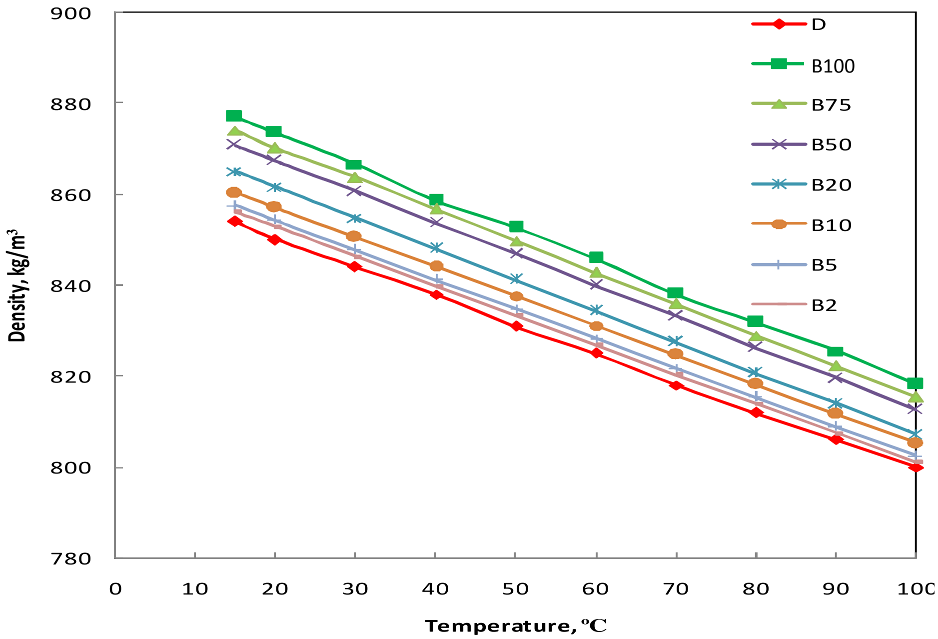

Figure 1. Variation of density of shea butter biodiesel-diesel fuel blends with temperature.

Table 6. Linear regression constants and regression coefficients for the density of the fuels using Equation (1).

Fuel	a	b	R^2
B100	887.0842	-0.689805	0.99958
B75	884.2321	-0.689587	0.99993
B50	881.1039	-0.684755	0.99999
B20	875.2437	-0.681508	0.99999
B10	870.0443	-0.648545	0.99999
B5	867.1529	-0.647440	0.99999
B2	865.7748	-0.648194	0.99999
D	863.0547	-0.635218	0.99962

The proposed equation for calculating pour point as a function is

$$T_{pp} = 256 + 0.2212 V_B + 0.000228 V_B^2 \quad (10)$$

where V_B is the volume fraction of biodiesel in the blend.

The measured and calculated values are in very good agreement. Equation (9) gave a regression coefficient (R^2) of 0.9985 while from Equation (10), R^2 = 0.9992.

Effect of temperature

The measured density as a function of temperature for the pure biodiesel, diesel and their blends are shown in Figure 1. In the figure, the points show the measured values while the lines are linear least square regression lines. In the temperature range studied, the biodiesel fuel and its blends with diesel fuel have a similar linear density-temperature relationship. The regression lines closely follow the measured data. Hence there are no qualitative differences in the behavior of the different blends. The experimental data correlated by the linear regressions are presented in Table 6. It can be seen from the table that the regression coefficient (R^2) is greater than 0.99 in all cases indicating that the linear least regression can represent very closely the density-temperature relationship for the fuels tested.

Figure 2 shows the viscosity-temperature curve for pure biodiesel and its blends. As can be seen in this figure, the curves show a similar trend for temperature variation, and the curves are almost identical with

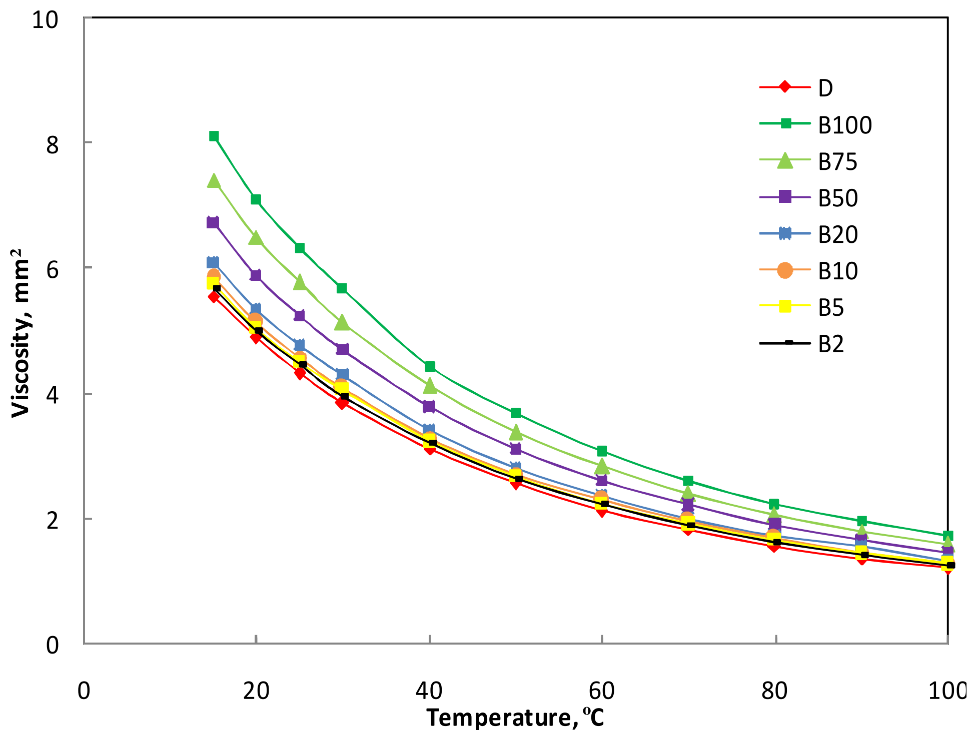

Figure 2. Variation of kinematic viscosity of shea butter biodiesel-diesel fuel blends with temperature.

Table 7. Linear regression parameters for viscosity of the fuels using Equation (6).

Fuel	A	B	C	R^2
B100	0.1834735	61.80109	-502.21520	0.98452
B75	0.1097112	61.18108	-495.93840	0.98452
B50	0.1097111	61.18108	-495.93840	0.98452
B20	-0.052505	60.32765	-491.28870	0.98411
B10	-0.081902	59.77445	-485.92190	0.98359
B5	-0.098879	59.88221	-487.05300	0.98322
B2	-0.106554	59.61703	-483.44900	0.98382
D	-0.1619898	60.62911	-491.37200	0.98455

increase in diesel content. This is due to the fact that the viscosity of the blends is much closer to the viscosity of diesel than shea butter biodiesel. The constants (A, B, C) and the regression coefficients for each regression curve in Figure 2 are given in Table 7.

Effect of biodiesel fraction

The variation in blend density with biodiesel content is shown in Figure 3. The measured values matched to points and the calculated values as a line from regression analysis. The density of the blend up to 20% biodiesel shows close matched points which widens with increase in biodiesel content. The density of the blend approaches that of diesel fuel as the biodiesel content decreases in the blend. Therefore, the density of the fuel blend increases with the increase in the amount of biodiesel in the blend. The prediction errors as indicated by AAD and MAD are presented in Table 8. The MAD obtained for estimating the blend density from Equation (3) is 0.114%.

Figure 4 shows the effect of biodiesel content on the viscosity of the blends. The viscosity of the blend increases as the biodiesel content in the fuel mixture increase. The viscosity does not change mostly for the blends up to 20% biodiesel as indicated by the close

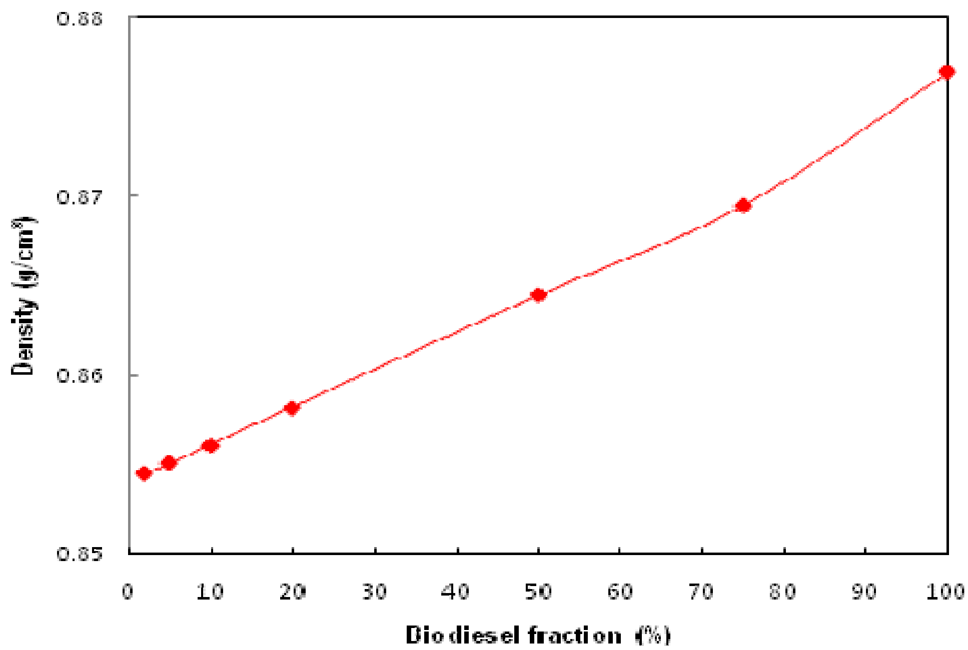

Figure 3. Variation of density of shea butter biodiesel-diesel fuel blends with biodiesel content.

Table 8. Prediction errors for shea butter biodiesel-diesel fuel blend.

Fuel	Density		Viscosity		Cloud point		Pour point	
	AAD (%)	MAD (%)	AAD (%)	MAD (%)	AAD (%)	MAD (%)	AAD (%)	MAD (%)
B100	0.011	0.114	0.002	0.023	0.0004	0.004	0.009	0.072
B75	0.010	0.104	0.0002	0.002	0.005	0.047	0.014	0.111
B50	0.005	0.046	0.015	0.145	0.011	0.085	0.009	0.075
B20	0.001	0.011	0.036	0.359	0.0004	0.004	0.014	0.115
B10	0.001	0.012	0.001	0.010	0.010	0.084	0.010	0.078
B5	0.002	0.023	0.014	0.138	0.0172	0.138	0.010	0.078
B2	0.004	0.035	0.002	0.021	0.003	0.023	0.000	0.000

matched points. The MAD obtained using the selected mixing rule for estimating the blend viscosity is 0.359%. The measured cloud and pour points of the fuel blends are presented in Figure 5. The cloud and pour points of biodiesel decrease with increase in diesel content. The MAD of 0.138 and 0.115% were obtained for cloud and pour points, respectively.

Conclusions

In this study, shea nut butter methyl ester was produced from shea butter to be used as a biodiesel fuel. A study was carried out to investigate how the basic flow properties: density, viscosity, cloud and pour points change when the biodiesel is blended with diesel fuel. Generalized and empirical equations, validated by using the measured values, were used for predicting the density and viscosities of the blends. Based on the analyses of the results obtained, the following conclusions can be drawn:

1. From the low values obtained for the AAD and MAD, it was found that the mixing rules were suitable for predicting the basic flow properties of shea butter biodiesel-diesel blends as a function of biodiesel concentration. The density and viscosity of the blend increased with increasing biodiesel content.
2. The statistical regressions properly fitted the variation of density and kinematic viscosity obtained from the experimental data. The biodiesel fuel and its blends had a linear density-temperature relationship similar to the diesel fuel. The kinematic viscosity decreased with increasing temperature.

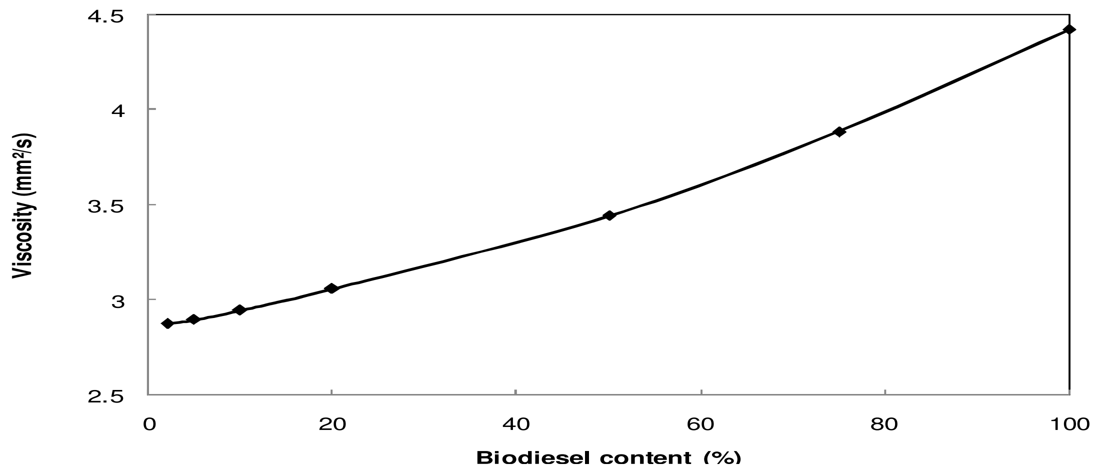

Figure 4. Variation of kinematic viscosity of shea butter biodiesel-diesel fuel blends with biodiesel content.

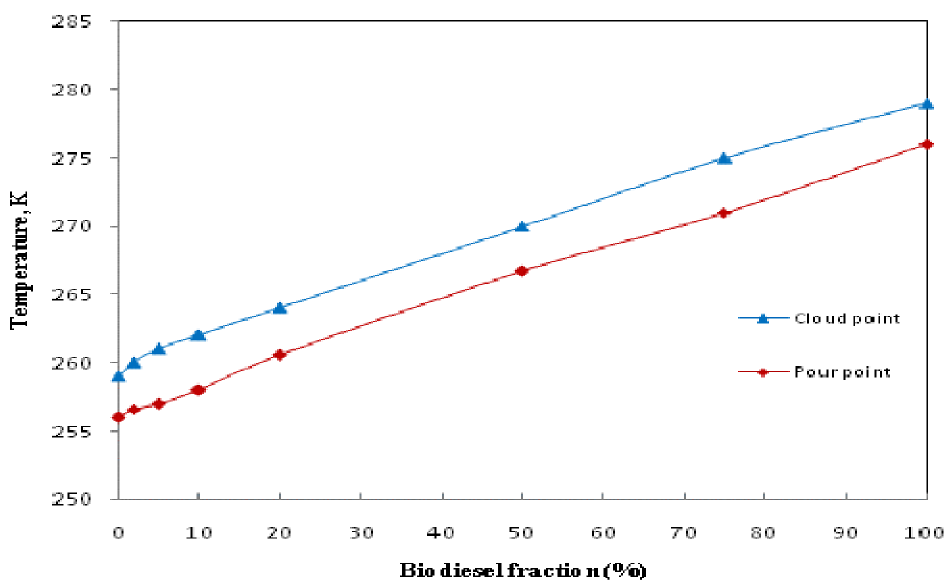

Figure 5. Variation of cloud and pour points with biodiesel content.

3. The empirical equations to predict both the cloud and pour points of biodiesel-diesel blends were developed. In all cases the cloud point and the pour point of the biodiesel decreased with increase in biodiesel content.
4. For the densities and viscosities measured, the prediction errors indicated by AAD and MAD are very small for all the tested fuels from 15 to 100°C.

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