International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.14 No.02, pp 268-282, 2021

Physico-chemical and thermophysical properties of ethyl biodiesel and biodiesel-diesel blend formulated from seed oil of *Afzelia africana* (L.) acclimated in Benin

Papin Sourou Montcho[1,2,3,*], Jean-Patrick Bazile[2], Guevara Nonviho[1,4], Cokou Pascal Agbangnan Dossa[1], Anna Chrostowska[3], David Bessieres[2] and Dominique Codjo Koko Sohounhloue[1]

[1]Research Unit on Molecular Interactions, Study and Research Laboratory in Applied Chemistry of the Polytechnic School of Abomey-Calavi, University of Abomey-Calavi (URIM / LERCA / EPAC / UAC), 01 BP: 2009 Cotonou , Benin.
[2]Laboratory of Complex Fluids and their Reservoirs, Multidisciplinary Institute for Applied Reseach in Petroleum Engineering, University of Pau and Pays de l'Adour (LFCR / IPRA / UMR 5150 / E2S UPPA), 64000, PAU, France.
[3]Institute of Analytical and Physical Chemistry Sciences for the Environment and Materials, University of Pau and Pays de l'Adour (IPREM / UMR 5254 / E2S UPPA), 64000, Pau, France.
[4]Pluridisciplinary Research Laboratory for Technical Education, National University of Science Technology Engineering and Mathematics, Lokossa BP 133, Benin.

Name of main: MONTCHO Papin Sourou*
Contact: anna.chrostowska@univ-pau.fr, david.bessieres@univ-pau.fr, csohoun@gmail.com

Abstract : Biodiesel is a credible substitute for diesel fuel. It is attracting more and more interest, especially its obtaining from unconventional seeds oils. The physical properties of seed oils of *Afzelia africana*, harvested in Benin, have been determined and its conversion to ethyl esters have been done. Thermophysical properties such as density, kinematic viscosity and isothermal compressibility of extracted seed oil, derivated biodiesel and biodiesel mixtures obtained with pure diesel were studied under wide ranges of pressure [0.1-40MPa] and temperature [293.15-353.15 K]. Experimental values of density were correlated using the TAIT-Like equation. The results revealed that *Afzelia africana* seeds have good lipid potential [33.33% (m/m)]. Similarly, the seed oil of *Afzelia africana* from Benin has a chemical composition in fatty acids that is different from that generally known. Its main fatty acid are palmitic (C16:0) (7.95%), stearic (C18: 0) (18.81%), oleic (C18:1) (19.08%), linoleic (18:2) (7.86%) and linolenic (C18:3) (29.99%) acids. Estimates of density and kinematic viscosity have identified pure biodiesel-diesel blends that meet ASTM D6751 and EN 14214 standards for their use in diesel engines as substitutes for fossil fuels.
Keywords : *Afzelia africana*, non edible oils, biodiesel-diesel blends, fatty acids and thermophysical properties.

DOI= http://dx.doi.org/10.20902/IJCTR.2021.140202

Introduction

Energy is one of the fundamental needs of our daily life and plays a leading role in industrial, transport, and electricity production sectors [1]. The transportation sector is the second-largest energy consumer worldwide after industry. It accounts for 30% of the total energy delivered worldwide and has grown steadily over the past 30 years. Over 97.6% of energy consumption in this sector comes from petroleum and fossil fuels that are exhaustible sources. They are also responsible for the environmental problems associated with their combustion. Many researchers have studied the possibility of using alternative fuels [2,3]. The sustainable production of renewable energies is the subject of a lively debate at a global level, since first-generation biofuels, mainly produced from food crops, have a limited capacity to achieve the objectives of biofuel production, mitigation climate change, and economic growth [4]. These concerns have led researchers to turn to the development of second-generation biofuels produced from non-food raw materials that offer the best opportunities in the long term. In fact, vegetable oils are renewable in nature and can be produced locally. In addition, their use has the advantage of reducing the cost of fuel and harmful emissions of greenhouse gas [5]. Indeed, unconventional vegetable oils can be used as fuel [6]. However, their low volatility and the large values of kinematic viscosity and associated density can cause problems when used in diesel engines [7,8]. On the other side, the alkyl esters formulated from vegetable oils by the transesterification reaction have kinematic viscosities and densities close to those of fossil diesel [9,10]. These methyl or ethyl esters commonly known as biodiesel must meet American Society for Testing and Materials (ASTM D 6751) and European Union (EN 14214) standards before being used as a substitute for fossil fuels in diesel engines. Better, the biodegradability and non-toxicity of biodiesels favor their use as an alternative fuel. More, the European Union directive recommends the use of at least 10% of biodiesel in mixture with fossil diesel or 100% biodiesel in the transport sector by 2030. Benin has a rich and varied ecosystem that remains in the under-exploited state including *Afzelia africana* (smith) called *Lingué* belonging to the family of Fabaceae. It's a tree that is widely distributed and also exploited for its wood. This wood is better known as *doussie*. It's a hardwood, sought after as lumber for construction and as energy wood [11]. The seeds of *Afzelia africana* would be used in Sierra Leone as harmful bait for fish, so it would therefore be unwise to use them in food [12]. This plant species risks disappearing if other farms such as those of seeds are not valued. Ajiwe et *al.* (1995) have extracted the oil from the seeds of *A. africana* in Nigeria and proceeded its physicochemical characterization [13]. They have also evaluated the thermal stability of its methyl esters [14]. In addition, the work carried out by Janat et *al.* (2009) in Côte d'Ivoire on *A. Africana* has shown the fatty acid composition of its vegetable oil [15]. However, to our knowledge, studies on the fuel potential and the complete characterization of the Benin plant species are not documented. Indeed, knowledge of the thermophysical and derivative properties under wide ranges of pressure and temperature of biodiesels and biodiesel-diesel mixtures is essential to assess the performance of engines. These properties are useful for better understanding the behavior of fuels during their injections and their combustion in engines. Among them, density and compressibility are of importance to optimize the injection process. Density is the fundamental property that influences the conversion of volume flow rate into mass biodiesel flow rate while the compressibility the fuel injection timing. Density depends both on the raw materials used for biodiesel fuel production and on the profile of the biodiesel methyl ester. The knowledge of viscosity is also an important concern as higher viscosity values tend to alter injection spray characteristics, resulting in fuel impregnement on the chamber. So, fuel which is too highly viscous can damage the fuel pump [16].

The few works reported in the literature for Benin plant species relate to the density and viscosity measured at atmospheric pressure. Unfortunately, very little data is available in the literature on these properties under conditions of elevated temperature and pressure [17,18].

In this context, this study details the main features of an ethyl- biodiesel produced from of *Afzelia africana* seed oil. We study the thermophysical profile for the pure ethyl biodiesel and mixtures of biodiesel with diesel. Data are also reported for the *Afzelia africana* seed oil.

Density measurements were carried out over extended ranges of pressure [0,1-40 (MPa)] and temperature [293,15 (K)- 353,15 (K)]. Isothermal compressibility was derivated from density data in the same experimental ranges. Additionally, kinematic viscosity was determined at atmospheric pressure for temperatures ranging from 293, 15 (K) to 353,15 (K).

Materials and methods

Materials, packaging, and vegetable oil extraction

The seeds of *Afzélia africana* **(Figure1)** were collected in the Park of the Pendjari between 11° 13 ′ 50 ″ North, 1° 31 ′ 36 ″ in the town of Tanguieta, in Northwestern Benin. They were dried, in the laboratory at 32 ± 2 °C, to a moisture content of 3.44±0.17% and freed from all impurities. These seeds were mechanically ground and the obtained powders were sieved and then kept in an oven (40 °C) up reducing their water and volatile matter contents. These powders were then extracted with hexane using the Soxhlet device for 6 hours at 69 °C, according to the NF V03-924 standard protocol. The extracted vegetable oil were then conditioned in a dry place, in opaque bottles and yields were evaluated by gravimetry.

Figure 1. Seeds of *A. Africana* acclimated in Benin

Quality indexes determination of *A. africana* seed oil

The water and volatile matter contents as well as the seed oil density were determined in accordance with DIN EN ISO 12937 and NF T 60-214 methods respectively. The acid (IA), peroxide (IP) and saponification (IS) indices (1) were determined respectively according to T 60-204, T 60-220 and T 60-206 standards. The iodine value (II) was evaluated by the Winkler method [19].The ester value (IE) has been calculated on the basis of the analytical data according to the formula [20].

$$IE = IS - IA \quad (1)$$

Production of ethyl biodiesel from *Afzelia africana* seed oil and biodiesel-diesel blends

The transesterification reactions were carried out in two stages. During the first step, the fatty acids in vegetable oil were esterified by homogeneous acid catalysis using a 30:1 molar ethanol:oil ratio in the presence of concentrated H_2SO_4 (1% m/m of oil) and moderate agitation (250 rpm at 78°C/1 hour). Then, the reaction were neutralized with 25% (m/m oil) of a sodium bicarbonate solution for 5 min with slow stirring and the phases have been separated in a separatory funnel. The ester obtained was dried and then filtered afterwards with a mixture of anhydrous sodium sulphate (Na_2SO_4). The residual solvent was evaporated under reduced pressure and the ester-rich phase was then weighed. The unreacted triglycerides and the partial glycerides (mono- and di-glycerides) contained in the ester-rich phase were transesterified in second step. The reaction was continued by varying the ethanol: oil molar ratio (6 and 8), the concentration of the KOH catalyst 1.1% (m/m oil) and the temperature 60 °C for 2 hours with moderate stirring (250 rpm). The final mixture was separated in a funnel separatory and the phase rich in esters was dried with anhydrous sodium sulfate and filtered on a filter paper.

Formulated ethyl biodiesel has been used to prepare diesel blends. The blends were made at 20°C in an Erlenmeyer flask with a lid and stirred at 250 rpm for 10 minutes. Ethyl biodiesel from *A. africana* was blended with diesel in three proportions: 5%, 10% and 20% by volume. These blends were named B5, B10, and B20, respectively.

Fatty acids analysis

Preparations of ethyl esters of fatty acids (EEFA)

400µL of 2N KOH solution (85%, Sigma Aldrich) in ethanol (99.8% for CPL-HP, Fischer Scientific) is mixed with 60 mg of oil. The mixture is then heated reflux at 70 °C with vigorous stirring. After 1 hour of reaction, mixture was cooled to room temperature. Then, 5 mL of n-heptane (Pesti-S grade, Biosolve) and 1 g of sodium sulfate were added to the mixture, vortexed for 10 seconds and left to stand for 20 min. The ethyl esters dissolved in heptane formed the upper layer which was separated from the decanted glycerol at the bottom of the aiming tube. 100 µL of ethyl esters extracted from the upper layer is diluted in 900 µL with n-heptane for analysis.

Analysis conditions

The fatty acid profile of the sample was carried out by a GC Scion 486 coupled to timsTOF HRMS BRUKER Daltonic equipped with an electrospray ionization source (GC-APCI). 1µL of diluted sample (20x in heptane) was injected in Split mode (x20) into the GC-TOFHRMS system, on a Restek RXi Sil-5MS column 30m long, 0.25 mm internal diameter and 0.25µm d film thickness. The injector temperature was 260 °C. The carrier gas used was helium at a constant rate of 4.0 mL.min-1. The programming of the initial oven temperature were 80 °C for 1min followed by an increase of 25 °C per minute at 140 °C, then a temperature increase by 20 °C per minute at 200°C and at last rise by 15 °C per minute to 310 °C with a Hold time of 5 min. The mass spectrometer worked in scan mode from 100 to 1000 m/z at 3 Hz. The temperature of the transfer capillary was 200 °C and the corona needle of 1800 nA. Chromatograms and mass spectra are analyzed using Bruker's Compass Data Analysis V4.3 software.

Density and kinematic viscosity measurements

Density measurements

The density (ρ) was measured with an Anton Paar K.G. DMA 45 vibrating tube density meter as a function of pressure and temperature for unconventional vegetable oil, ethyl biodiesel and pure biodiesel-diesel blend. An additional cell DMA 512 has been adapted to this instrument, which can measure under pressure up to 40 MPa. In this study, the apparatus allowed us to perform measurements by varying the temperature from 293.15 to 353.15 K and the pressure from 0.1 to 40 MPa. The DMA 45 was connected to an mPDS 2000V3, allowing us to measure the vibration period with a high certain accuracy. A Julabo Polystat 36 thermostatic bath is used to control the temperature of the vibrating tube cell. The temperature is measured inside the cell by an AOIP thermometer PN 5207 with an uncertainty of 0.05 K. A volumetric piston pump is used to apply pressure to the system, which is measured by an HBM PE 200/2000 sensor with an uncertainty of 0.1 %. Before and after each handling (sample loading), the density meter and all capillaries are cleaned with petroleum hexane ether to remove any traces of residues of the previously investigated substance. Once this cleaning process is completed, a vacuum is applied to the system before introducing the sample to be studied. When thermal equilibrium is reached, the vibration period of the cell is determined at different pressures, starting with 0.1 MPa, followed by the highest pressures. Then the temperature of the liquid bath is changed and a new isotherm is studied.

In this type of device, the density is related to the period of vibration by the equation (2):

$$\rho(p,T) = A(p,T)\zeta^2(p,T) - B(p,T) \qquad (2)$$

With ρ (p, T) the density of the sample, ζ (p, T) the period of oscillation, A (p, T) and B (p, T) two characteristic parameters of the instrument.

As far as calibration is concerned, we have opted for the method used by Comuñas *et al*. (2008) which is more suitable for our field of investigation and is based on the hypotheses made by Lagourette et *al*. 1992 [21,22].

Taking into account these hypotheses, the equation (3) can be written:

$$\rho(T,P) = \rho_{eau}(T,P) + \rho_{eau}(T\,;0{,}1\text{MPa})\left[\frac{\zeta^2(T,P) - \zeta^2_{eau}(T,P)}{\zeta^2_{eau}(T\,;\,0{,}1\text{MPa}) - \zeta^2_{vide}(T,P)}\right] \qquad (3)$$

The estimated uncertainty of the measured pressure was ± 0.015 MPa (Presens Precise Gold Plus pressure transmitter) and the estimated uncertainty of the determined density was ± 0.5 kg m−3 (i.e., around 0.05% for density close to water density).

Kinematic Viscosity measurements

The kinematic viscosity of our samples was determined with a SCHOTT-GERÄTE Ubbelohde viscometer. A kinetic energy correction is applied depending on the diameter of the capillary tubes used. For this purpose, approximately 15 mL of the filtered sample was introduced into the reservoir (capillary tube). The maximum filling volume is limited by the markings on the reservoir. After filling, the viscometer is hung with its holder in a transparent thermostat from SCHOTT-GERÄTE. In order to avoid measuring errors of the viscometer, the temperature in the thermostat has been kept constant at ± 0.01°C. Each capillary tube is provided with a calibration certificate, but the calibration of the capillary viscometer was checked at several temperatures using "Viscosity Reference Standard" fluid S20 provided by ColeParmer. The uncertianty is less than 1%.

Results and discussion

Quality indexes and fatty acids profile of *Afzelia Africana* seeds oils from Benin

Quality indexes of *Afzelia Africana* from Benin

Table 1 presented the quality indexes of seed oils extracted from *A. africana* seeds acclimated in Benin.

Table 1 : Quality indexes of *Afzelia Africana* seeds oils from Benin

Properties	This study	Ajiwe et *al*.[12] Janet et *al*. [14]
Extraction yield (%, g/g)	33.23 ± 3.26	19.96-29.1
Acid index (mg KOH/g-Oil)	6.75 ± 0.16	5.61-18.29
Saponification Index (mg KOH/g-Oil)	186.97 ± 5.04	185.32 ± 0.12
Iodine value (mg I_2/100 g-Oil)	114.66 ± 0.64	109.13 ± 0.04
Peroxide value (meq O_2/Kg-Oil)	7.24 ± 0.58	-
Calculated ester index (mg KOH/g-Oil)	180.21 ± 5.19	179.71 ± 0.10

Afzelia africana seeds from Benin revealed high oil extraction yield (33.23 ± 3.26%). Ajiwe et *al.*, Ene-Obong and Carnovale found lower yields (19.96-29.1%) of seed oil from *Afzelia africana* seeds, harvested in Nigeria [12,23]. Lipid potential of the seeds could depend on several parameters such as those related to origin, seed maturity and edaphic conditions [24]. However, considering the seed oil content (> 30%) of *Afzelia africana* seeds harvested in Benin, their use as fuel oil could be considered [25].

While the acid index evaluates the degradation of vegetable oil by hydrolysis, depending on its free fatty acids, the peroxide index makes it possible to briefly assess its oxidative stability. The acid (6.75 ± 0.16 mg KOH/g-oil) and peroxide (7.24 ± 0.58 meq O_2/Kg-oil) indices of the oil extracted from *Afzelia africana* seeds from Benin are lower than those reported in previous studies. However, these indices are well above the threshold values recommended by the Codex-alimentarus for food vegetable oils. This reinforces our reluctance for the food uses that could be made of this oil [26].

The saponification and ester indices of the seed oil of *Afzelia africana* are 186.97 ± 5.04 mg KOH/g-oil and 180.21 ± 5.19 mg KOH/g-oil respectively. It is inferred that this seed oil is richer in short-chain fatty acids.

The iodine index of the studied seed oil is 114.66 ± 0.64 mg I_2/100 g-Oil. This value is close to the limit (120 g I_2/100 g-oil) defined by the EN 14214 23 standards. It infers that the oil of *Afzelia africana* can be classified as a batch of semi-dried linoleic type oils [27].

Fatty acid composition of vegetable oil and its influence on fuel properties

The fatty acid composition of a seed oil have a great influence on its fuel properties. Fatty acids of *Afzelia africana* seed oil from Benin is recorded in the **Table 2**.

Table 2: Fatty acid composition of unconventional seed oil

Fatty acids and sub-classes	**Skeleton**	**This study (%)**	**Other studies (%) [12,13]**
Capric	C10:0	0.26	-
Undedecylic	C11:0	1.56	-
Lauric	C12:0	1.50	0.67- 0.91
Tridecylic	C13:0	1.72	-
Myristic	C14:0	1.10	0.79-1.54
Palmitic	C16:0	7.95	6.97-10.53
Stearic	C18:0	18.81	21.97-25.59
Arachidic	C20 :0	0.70	-
Behenic	C22:0	1.57	-
Tricosylic	C23:0	0.89	-
Lignoceric	C24:0	0.39	-
Saturated Fatty Acids: SFA		**36.45**	**32.04-38.57**
Myristolic	C14:1	0.79	-
Palmitolic	C16:1	1.30	-
Oleic	C18:1	19.08	12.65-13.39
Gondoïc	C20 :1	0.66	-
Monounsaturated Fatty Acids: MUFA		**21.83**	**12.65-13.39**
Linoleic	C18:2	7.86	0.01-6.66
Linolenic	C18:3	29.99	41.25-42.14
Homo-γ Eicosatrienoic	C20:3	3.88	-
Polyunsaturated Fatty Acids: PUFA		**41.72**	**41.25-48.04**
Total saturated fatty acids		**36.45**	**38.51**
Total unsaturated Fatty Acids		**63.55**	**61.49**

- : Fatty acids not quantified

The seed oil of *Afzelia africana* is rich in polyunsaturated fatty acids (63.55%) with a dominance of linolenic fatty acids (29.99%). Knothe described that as the number of unsaturations increases, so does the viscosity of fuels. However, temperature variation can also influence this parameter [28]. The seed oil of Afzelia africana of our study has also a good proportion on saturated fatty acids (36.45%), mainly on stearic acid (18.81%). Monounsaturated fatty acids (21.83%) are greatly represented by oleic acid (19.08%). The seed oil of *Afzelia africana* is generally very rich in linolenic acid (41.25-42.14%). The vegetable oil of *Afzelia africana* extracted from Benin has the particularity of a much smaller proportion on linolenic acid but higher proportion on oleic acid. Linolenic acid can cause low oxidative stability in vegetable oils and a reduction in its quantity could optimize the energy properties of biofuels. At the same time, a decrease in linolenic acid composition added to an increase in oleic acids could have many industrial applications [29]. The proportion of saturated fatty acid (36.45%) in the vegetable oil of *Afzelia africana* harvested in Benin is close to the values reported in the literature [12]. A good cetane number has been associated with fuel vegetable oils with a good composition of saturated fatty acids such as palmitic and stearic acids [30].

Density measurements

Density (ρ) is an important parameter that influences the dissolution of fuel injected into the engine cylinder. Table 3 shows the density of *Afzelia africana* seed oil, ethyl biodiesel and biodiesel-diesel blends (B5, B10 and B20) formulated in this way by varying the pressure from 0.1 to 40 MPa and in a temperature range from 293.15 to 353.15 K.

Table 3: Density (ρ) of seed oil (VOAa), ethyl biodiesel (B100) and biodiesel-diesel blends of *Afzelia africana* of Benin, as a function of temperature (T) and pressure (P)

Pression / MPa		Temperature /K			
		293.15	313.15	333.15	353.15
		Density ρ, (Kg/m^3)			
VOAa					
0.1		933.32	918.79	906.80	891.29
10		938.34	926.16	911.36	897.95
20		943.74	932.31	916.25	904.39
30		948.37	937.39	921.20	910.34
40		953.26	942.09	927.97	915.66
B100					
0.1		908.59	893.18	878.40	862.66
10		914.09	899.26	885.35	870.67
20		919.29	905.01	891.46	877.49
30		924.31	910.63	897.33	884.02
40		929.09	915.71	903.06	890.02
B5					
0.1		837.62	823.38	808,88	794,48
10		843.73	830.03	816,33	802,94
20		849.41	836.34	823,15	810,17
30		854.60	841.99	829,34	817,16
40		859.51	847.49	835,39	823,42
B10					
0,1		839.88	825.24	810.83	795.93
10		845.80	832.04	818.28	804.54
20		851.57	838.25	825.29	812.31
30		856.71	844.19	831.68	819.39
40		861.77	849.69	837.54	825.51
B20					
0.1		848.32	834.28	819.40	802.96
10		855.12	841.03	826.70	813.32
20		860.26	847.00	833.43	820.65
30		865.45	852.55	839.72	827.70
40		870.32	857.91	844.75	833.92

Figure 2 and **3** show the effect of temperature and pressure on the density of the studied oil, of its formulated ethyl biodiesel and of the biodiesel-diesel blends (B5, B10 and B20). As one would expect, *A. africana*'s seed oil is denser than its biodiesel. It has also been observed that at constant temperature, increasing the pressure from 0.1 MPa to 40 MPa with a 10 MPa step increase the density of our samples. On the other hand, when measurements were made at constant pressure, as a function of temperature, the density decreases. The variation in density as a function of pressure and temperature is virtually identical for all biodiesel-diesel blends. In fact, the density values of each of the formulated biodiesels as a function of temperature and pressure make it possible to estimate the quality of the spraying of these biodiesels in engine combustion chambers. Very little data exists on the evaluation of the density of ethyl biodiesels as a function of pressure and temperature to compare with our experimental data. Nevertheless, Rodríguez-Antón et *al.* (2008) were able to report experimental data on methyl esters of rapeseed and petroleum diesel at atmospheric pressure and at 293.15 K. Thus, they found densities of 883 kg/m^3 for rapeseed methyl esters and 835 kg/m^3 for petroleum diesel [31]. The density of studied seed oil is greater than 0.900 kg/m^3 recommended by European standards EN 14214 for pure fuel oils. It is important to note that the density increases with the length of the chain (number of carbon atoms) and with the increase in the number of double bonds contained in the fatty acids of this oil [27]. On the other hand, the density values measured at temperatures greater than or equal to 313.15K depending on the pressure (0.1MPa - 40MPa) for biodiesel derived from the vegetable oil of *Afzelia africana* and for mixtures of

5%, 10% and 20% by volume of biodiesel formulated with pure diesel are in accordance with the value recommended by standards EN 1424 and ASTM (860 kg/m^3 -900 kg/m^3).

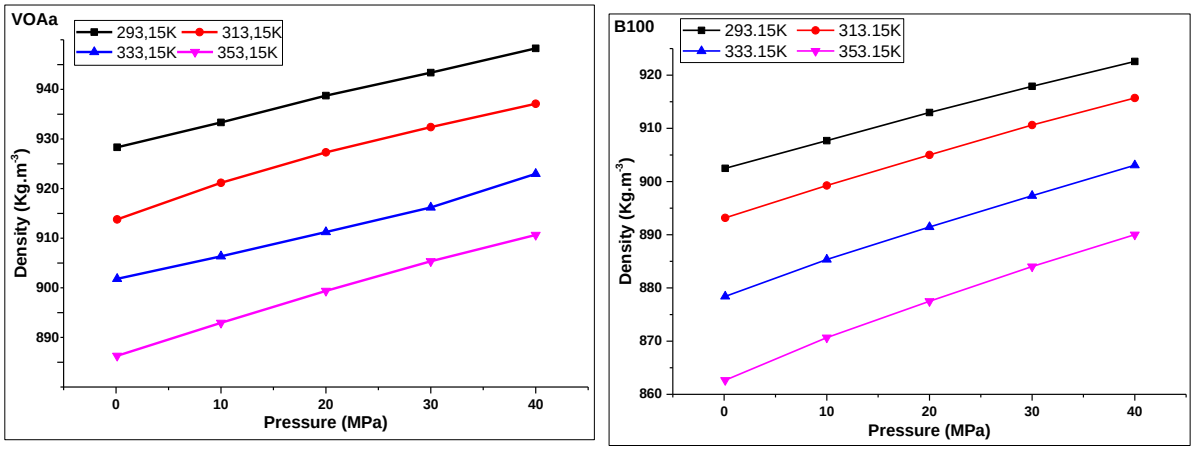

Figure 2. Effect of temperature and pressure on the density of vegetable oil (VOA) and pure biodiesel (B100)

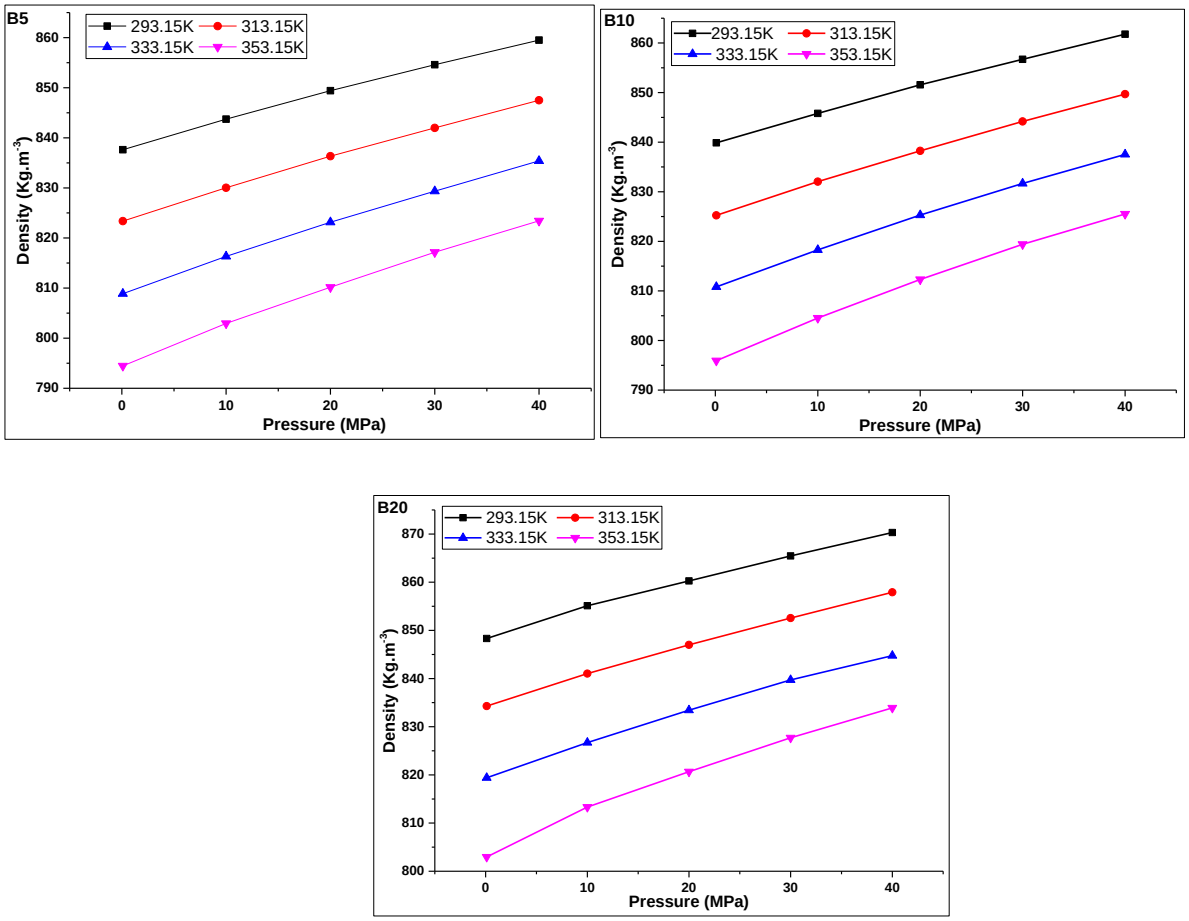

Figure 3. Effect of temperature and pressure on the density of biodiesel-diesel blends (B5, B10 and B20)

The density values for biodiesel and biodiesel-diesel blends betwen temperatures 298.15 - 353.15 K and pressures ranging from 0.1 to 40 MPa were summarized in Table 3 were correlated using the TAIT-Like equation (4).

$$\rho(T,p) = \frac{\rho_0(T\,;\,0.1\,MPa)}{1-\rho_0(T\,;0.1\,MPa)A\ln(1-\frac{p-0.1}{B(T)})} \qquad (4)$$

With ρ_0(T; 0.1 MPa) the density of the sample at the reference pressure. A and B are two temperature-independent adjustable parameters (5).

$$\rho_p(T) = A_0 + A_1\mathrm{T} + A_2T^2 + A_3T^3 \quad (5)$$

The comparison of the experimental density values and those found with the TAIT-Like correlation was made using the mean absolute deviation (AAD), the maximum deviation (DMax) and the mean deviation (Bias). These AAD, DMax and Bias parameters were determined from the equations defined below (6, 7, 8):

$$\mathrm{AAD} = \frac{100}{\mathrm{N}} \sum_{\mathrm{i}=1}^{100} \left| \frac{\rho_{\mathrm{i}}^{\mathrm{exp}} - \rho_{\mathrm{i}}^{\mathrm{calc}}}{\rho_{\mathrm{i}}^{\mathrm{exp}}} \right|; \quad (6)$$

$$DMax = Max\left(100 \left| \frac{\rho_i^{exp} - \rho_i^{calc}}{\rho_i^{exp}} \right|\right); \quad (7)$$

$$Bias = \frac{100}{N} \sum_{i=i}^{N} \frac{\rho_{\mathrm{i}}^{\mathrm{exp}} - \rho_{\mathrm{i}}^{\mathrm{calc}}}{\rho_i^{exp}} \quad (8)$$

With N the number of experimental data for each sample, ρ^{exp} and ρ^{calc} respectively the experimental density and the density obtained with equation (3).

Isothermal compressibility of ethyl biodiesel and pure diesel blends

The parameters of the TAIT-Like equation as well as AAD, DMax and Bias determined with the density correlation are grouped in **Table 4**. Density measurements along the isotherms (298.15 - 353.15 K) and as a function of pressure of 0.1-40 MPa, allow the estimation of isothermal compressibility.

Table 4: Parameters and deviation obtained from the TAIT equation for density correlation and calculation of derived properties

Coefficients	B5	B10	B20	B100
A_0 (g.cm^{-3})	0.787122722	1.53506466	1.40477544	0.692335055
A_1 (g.cm^{-3}.K^{-1})	0.001687669	-0.0052703	-0.00436199	0.001872306
A_2 (g.cm^{-3}.K^{-2})	-7.36551×10^{-6}	1.4245×10^{-5}	1.2696×10^{-5}	-3.9375×10^{-6}
A_3 (g.cm^{-3}.K^{-3})	7.49136×10^{-9}	-1.4859×10^{-8}	-1.464×10^{-8}	-
ρ_0 (g.cm^{-3}) à 293,15	0.837618922	0.83987592	0.84831742	0.902486832
A (MPa)	-0.082548797	-0.1119324	-0.07372371	-0.106497732
B (MPa)	89.60242434	128.602412	80.1030041	156.6024093
AAD (%)	0.00392356	0.006612694	0.002325367	0.18206635
DMax (%)	0.01103486	0.011642682	0.00565426	0.98480418
Bias (%)	-0.00214265	-0.006642630	0.000124368	-0.000039189

Isothermal compressibility

The coefficient of isothermal compressibility is an important volumetric property of fluids. It helps to understand the thermodynamic behavior of fluids in engines. Based on the results of density measurements of biodiesel-diesel blends presented above (Table 3), we were able to calculate the isothermal compressibility as a function of pressure (0.1 to 40 MPa) in the temperature range (298.15 to 353.15 K) using the parameters of the TAIT-Like equation. The coefficient of isothermal compressibility depends on the structure of the fuel and indicates the trend in density as a function of pressure. The coefficient of isothermal compressibility (χ_T) was calculated using equation (3) and the following expression (9):

$$\chi_{\mathrm{T}} = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial \mathrm{P}}\right)_{\mathrm{T}} \quad (9)$$

By replacing equation (3) in the expression of equation (8), we obtain (10):

$$\chi_T = \frac{A\rho_0(T)}{(B + p - 0.1\ \text{MPa})\left[1 + A\rho_0 \ln\left(1 + \frac{p-0.1\ \text{MPa}}{B}\right)\right]} \quad (10)$$

The values of the isothermal compressibility coefficient calculated from equation (9) are summarized in Table 5. Isothermal compressibility coefficient estimates for formulated biodiesel and pure biodiesel-diesel blends were made by varying the pressure from 0.1 to 40 MPa and for isotherms of 293.15, 313.15, 333.15 and 353.15 K (**Table 5**).

Table 5: Isothermal compressibility coefficients for ethyl biodiesel (B100) and biodiesel-diesel blends (B5, B10 and B20)

Pressure (MPa)		Blends		Temperature (°C)	
		293.15	313.15	333.15	353.15
		$10^3\ k_T/MPa^{-1}$			
B100					
0.1		0.6137	0.7244	0.7990	0.9560
10		0.5807	0.6683	0.7400	0.8547
20		0.5509	0.6202	0.6891	0.7727
30		0.5241	0.5788	0.6450	0.7056
40		0.5000	0.5428	0.6064	0.6497
B5					
0.1		0.7717	0.8674	0.9672	1.1386
10		0.7000	0.7827	0.8758	0.9916
20		0.6403	0.7130	0.8002	0.8783
30		0.5904	0.6550	0.7371	0.7889
40		0.5479	0.6061	0.6837	0.7167
B10					
0.1		0.7310	08642	0.9762	1.1769
10		0.6835	0.7886	0.8841	1.0181
20		06417	0.7250	0.8078	0.8972
30		0.6050	0.6714	0.7442	0.8027
40		0.5725	0.6254	0.6903	0.7269
B20					
0.1		0.7808	0.8409	0.9777	1.3234
10		0.7000	0.7585	0.8488	1.0837
20		0.6342	0.6908	0.7499	0.9178
30		0.5800	0.6345	0.6722	0.7969
40		0.5347	0.5871	0.6095	0.7049

Based on the values presented in this **Table 5** and the graphs in **Figure 4**, it was found that the isothermal compressibility coefficient (χ_T) of formulated ethyl biodiesel decreased when the pressure increases at constant temperature. On the other hand, this coefficient increases with temperature at constant pressure. The calculated isothermal compressibility coefficient values ranged from (0.500 to 0.956) 10^{-3} MPa-1. These recorded isothermal compressibility values corroborate those of (0.461 - 1.377) GPa^{-1} sunflower methyl and ethyl esters and are consistent with literature data [32]. As expected and similar to the coefficient of compressibility of formulated ethyl biodiesel, the isothermal compressibility of biodiesel-diesel blends (B5, B10 and B20) decreases with pressure and increases with temperature at constant pressure. In addition, the largest variation in compressibility is associated with B20 (0.535-1.323)10^{-3} MPa^{-1} followed by B10 (0.572-1.177) 10^{-3} MPa^{-1} and B5 (0.548-1.139) 10^{-3} MPa^{-1} in that order.

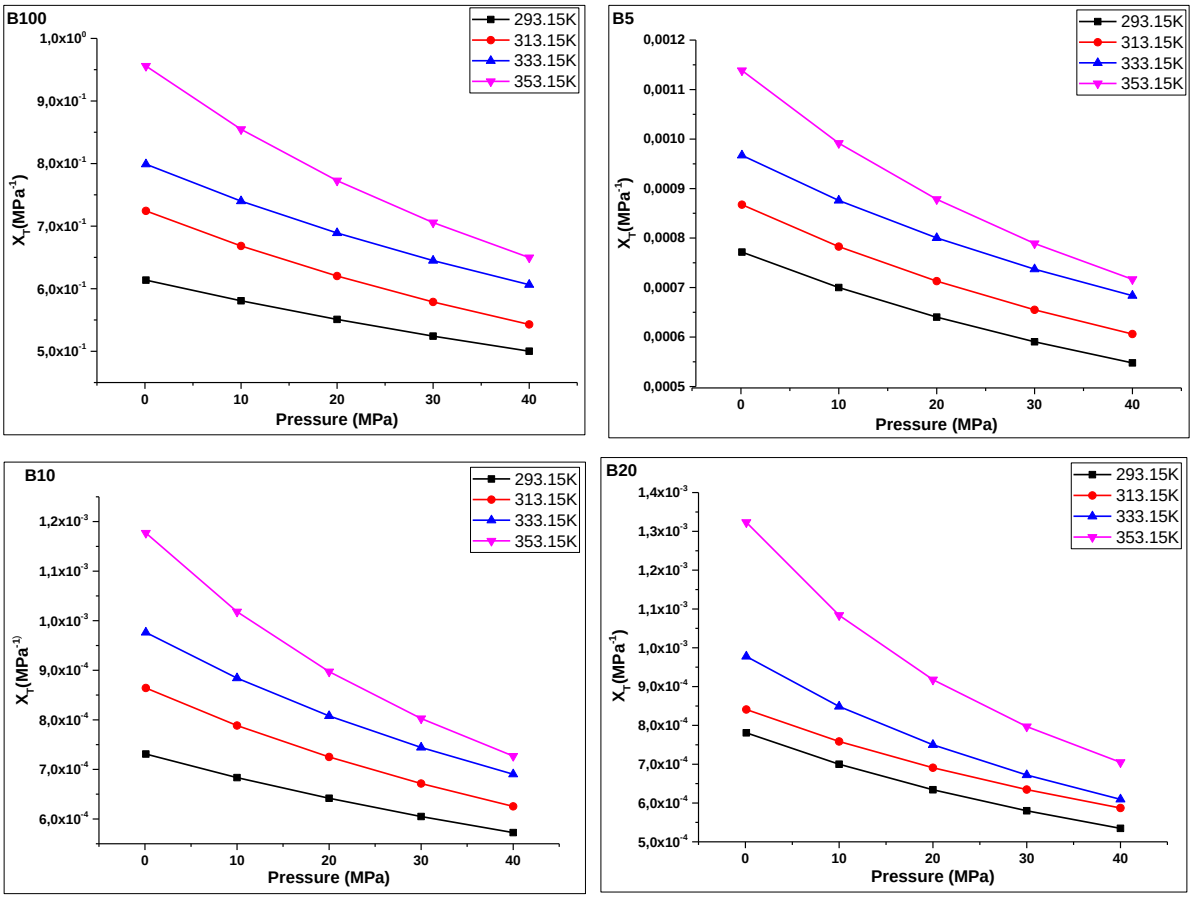

Figure 4. Variation of isothermal compressibility coefficient as a function of pressure at 293.15 K; 313.15 K; 333.15 K and 353.15 K

Measurement of kinematic viscosity

Viscosity is also an important physical property of biofuels. It allows a better appreciation of the conditions under which fuel is injected into engines. Viscosity measurements were carried out by varying the temperature from 293.15 to 373.15 K **(Table 6)**.

Table 6: Measurements of kinematic viscosity as a function of temperature.

Temperature (K)	VOAa	B100	B5	B10	B20
293.15	106.77	14.12	4.35	4.76	6.00
303.15	76.04	10.35	3.57	3.88	4.86
313.15	45.30	6.58	2.78	2.99	3.71
323.15	33.37	5.23	2.38	2.54	3.14
333.15	21.44	3.87	1.97	2.09	2.56
343.15	17.22	3.35	1.76	1.84	2.23
353.15	12.99	2.83	1.55	1.59	1.90
363.15	8.81	2.59	1.42	1.42	1.74
373.15	4.64	2.36	1.30	1.32	1.58

Figure 5 shows the change in kinematic viscosity of seed oil and formulated ethyl biodiesel as a function of temperature. First, it should be noted that ethyl esters of vegetable oils have the advantage of having a much lower kinematic viscosity compared to the corresponding seed oils. The kinematic viscosity of a seed oil can be used to monitor biodiesel production. Thus, it can be seen that the kinematic viscosity curves of seed oil and biodiesel (ethyl esters) decrease as the temperature increases. Furthermore, we have noticed that the ethyl ester viscosity of seed oils decreases more rapidly than that of pure diesel. It has been observed that from 313.15 K onwards, the kinematic viscosity of ethyl biodiesel is very close to that of pure diesel evaluated under the same conditions. Like density, kinematic viscosity is an important fuel property which is related to the fatty acid composition of seed oil and therefore that of formulated biodiesel. Indeed, an oil rich in unsaturated fatty acids has a lower kinematic viscosity compared to an oil which contains a large composition of saturated fatty acids [32]. Previous work has shown that the configuration of the double bond influences viscosity (configuration of the cis double bond giving a lower viscosity than trans) while the position of the double bond affects viscosity less [33]. *Afzelia africana* vegetable oil contains a proportion of unsaturated fatty acids, the most predominant of which are linolenic (29.99%) and oleic (19.08%) acids. This fatty acid composition of this oil gives the oil good fluidity, therefore the derived biodiesel, good kinematic viscosity. Kinematic viscosity values of many fatty acid methyl esters have been reported [34,35].

Figure 6 shows the influence of temperature on the kinematic viscosity of biodiesel-diesel blends and the corresponding ethyl biodiesels. It shows that the kinematic viscosity decreases with the proportion of biodiesel in the blend and temperature. Thus, the viscosity of the B5 blend is lower than that of the B10, B20 and B100 (100% biodiesel) blends in that order. From all of the above, we can conclude that the kinematic viscosity of all blends meets ASTM and EN 14214 standards and can be considered as substitutes for fossil fuels in diesel engines. Furthermore, it has been noticed that the viscosity of biodiesel-diesel blends has improved significantly with increasing temperature.

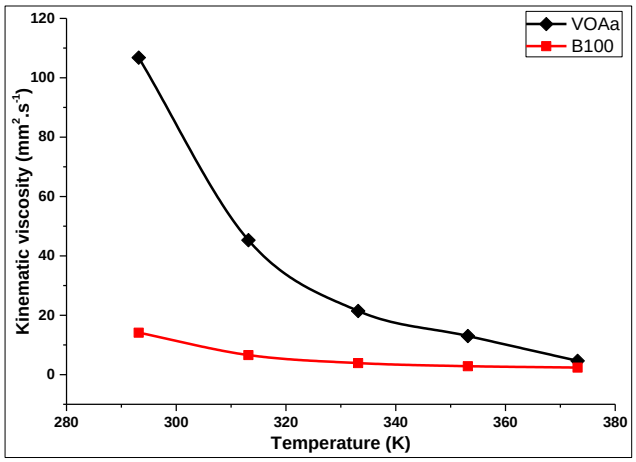

Figure 5. Kinematic viscosity variation as a function of temperature: vegetable oil (VO) and ethyl biodiesel (B100)

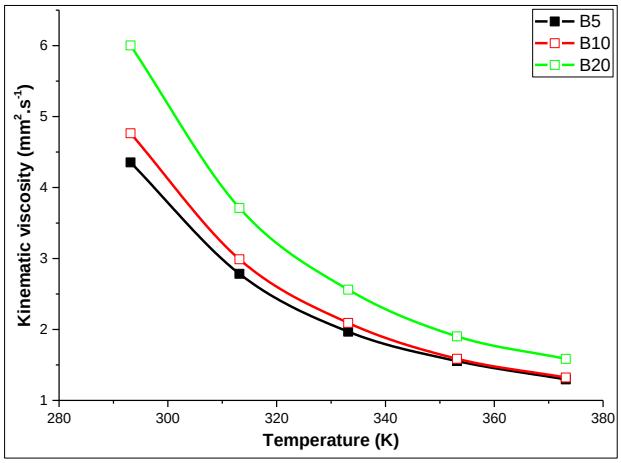

Figure 6. Effect of Temperature on Kinematic Viscosity of Biodiesel-Diesel Blends (B5, B10 and B20)

Conclusion

A. africana seeds from Benin have a high lipid potential (30%). The two main fatty acids identified in *A. africana* oil using gas phase Chromatography coupled with mass spectrometry are linolenic acids (29.99%) and oleic acids (19.08%) (18.81%). As far as the quality of this unconventional seed oil is concerned, the values of the quality indices are close to those of fuels.

The density and kinematic viscosity were measured for temperatures between 293.15 and 353.15 K and pressures ranged from 0.1 to 40 MPa. Of all the above, the density and kinematic viscosity of diesel and biodiesel-diesel blends (B5, B10 and B20) decrease with the increase in temperature. On the other hand, they increase with the increase in the amount of ethyl biodiesel in each blend. Estimates of density and kinematic viscosity have identified pure biodiesel-diesel blends that meet ASTM D6751 and EN 14214 standards for their use in diesel engines as substitutes for fossil fuels.

The insulated compressibility coefficient was calculated for each of the biodiesel-diesel mixtures formulated from the TAIT-Like equation. In general, the insulated compressibility coefficient of all our samples decreases with increased pressure along the isotherms. The three B5 blends give satisfactory values comparable to that of pure diesel.

The estimation of density, kinematic viscosity, the isothermal compressibility of biodiesel and biodiesel-diesel blends, will be necessary for industrial applications and the development of high-power engines.

Acknowledgements

The authors wish to acknowledge French government via Cooperation and cultural Action service (SCAC) near Benin (Cotonou) award of a graduate scholarship. This work was carried out as part of a doctoral thesis jointly supervised by University of Pau and the Pays de l'Adour (France) and University of Abomey-Calavi (Benin).

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Dharma S, Masjuki HH, Ong HC, Sebayang, AH, Silitonga, AS, Kusumo, F, Mahlia, TMI. Optimization of biodiesel production process for mixed *Jatropha curcas–Ceiba pentandra* biodiesel using response surface methodology. Energy Conversion and Management 2016; 115:178-190
2. Atabani AE, Silitonga AS, Badruddin IA, Mahlia TMI., Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renewable and sustainable energy reviews 2012, 16(4), 2070-2093.
3. Sidohounde A., Dossa CPA., Nonviho G., Montcho S.P., Sohounhloue DCK. Biodiesel potentials of two phenotypes of *Cyperus esculentus* unconventional oils. Journal of Petroleum Technology and Alternative Fuels 2018, 9(1), 1-6
4. Shikha K., Chauhan Y.R. Biodiesel production from non-edible-oils: a review. Journal of Chemical and Pharmaceutical Research 2012, 4(9), 4219-4230.
5. Goldemberg J. Environmental and ecological dimensions of biofuels. In Proceedings of the conference on the ecological dimensions of biofuels March 2008, Washington, DC (Vol. 10).
6. Sahafi SM, Ahmadibeni A, Talebi AF, Goli SAH, Aghbashlo M & Tabatabaei M. Seed oils of Sisymbrium irio and Sisymbrium sophia as a potential non-edible feedstock for biodiesel production, Biofuels 2018, 1-9. DOI: 10.1080/17597269.2018.1457315
7. Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresour Technol 2006; 98: 1167–75.
8. Shay EG. Diesel fuel from vegetable oils: status and opportunities. Biomass Bioenergy 1993: (4):227–42.
9. Knothe G, Van Gerpen J, Krahl JE. The biodiesel handbook. Illinois: AOCS Press; 2005.
10. Pullen J, Saeed K. Factors affecting biodiesel engine performance and exhaust emissions – Part I: review. Energy 2014; 72:1–16.
11. Hawthorne WD. Ecological profiles of Ghanaian forest trees. Tropical forestry papers 1995, (29).
12. Neuwinger HD. Plants used for poison fishing in tropical Africa. Toxicon 2004, 44(4), 417-430.

13. Ajiwe VIE, Okeke CA, Agbo HU. Extraction and utilization of *Afzelia africana* seed oil. Bioresource technology 1995, 53(1), 89-90.
14. Ogbu IM, Ajiwe VIE. FTIR studies of thermal stability of the oils and methyl esters from *Afzelia africana and Hura crepitans* seeds, Renewable Energy 2016, 96 :203-208
15. Janat A, Mamyrbékova-békro Bamba S., Akaffou S., & Bekro YA. Caracterisation de la matiere grasse extraite des amandes de *Afzelia africana* (fabaceae-caesalpinioideae) de côte d'ivoire. Rev Ivoir Sci Technol 2009, 13, 191-198.
16. Bessières D, Bazile JP, Nguyen Thi Tanh X., García-Cuadra, F, Acien, FG, Thermophysical behavior of three algal biodiesels over wide ranges of pressure and temperature. Fuel 2018, 233: 497–503
17. Baroutian S, Aroua MK, Raman AAA, Sulaiman NMN. Viscosities and densities of binary and ternary blends of palm oil + palm biodiesel + diesel fuel at different temperatures. J Chem Eng Data 2010;55: 504–7.
18. Tate RE, Watts KC, Allen CAW, Wilkie KI. The densities of three biodiesel fuels at temperatures up to 300°C. Fuel 2006; 85: 1004–9.
19. Bothon, F. T., Montcho, P. S., Nonviho, G., Agbangnan Dossa, C. P., Tchiakpe, L., Adomou, A. A., & Avlessi, F. (2020). Physicochemical Variability and Biodiesel Potential of Seed Oils of Two Hibiscus sabdariffa L. Phenotypes. *ACS omega*, *5*(40), 25561-25567.
20. MONTCHO P S, TCHIAKPE L, NONVIHO G, BOTHON F T D, SIDOHOUNDE A, DOSSA C P A, ... & SOHOUNHLOUE D C K. Fatty acid profile and quality parameters of *Ceiba pentandra* (L.) seed oil: A potential source of biodiesel. *Journal of Petroleum Technology and Alternative Fuels* 2018, *9*(3), 14-19.
21. Comunas MJP, Bazile JP, Baylaucq A, Boned C. Density of diethyl adipate using a vibrating densimeter from 293.15 to 403.15 K and up to 140 MPa densimeter calibration and measurements. Chem Eng Data 2008; 53:986–94.
22. Lagourette B, Boned C, Saint-Guirons H, Xans P, Zhou H. Densimeter Calibration Method Versus Temperature and Pressure. Meas. Sci. Technol. 1992, 3, 699
23. Ene-Obong HN, & Carnovale E. Nigerian soup condiments: Traditional processing and potential as dietary fibre sources. Food Chemistry 1992, 43(1): 29-34.
24. Kaimal TNB & Lakshminarayana G. Changes in lipids of maturing Ceiba pentandra seeds. Phytochemistry 1972, 11(5):1617-1622.
25. Alabi, K. A. Chemical Characterization of Soluble Soap Prepared from Milkbush (Theretia peruviana) Seed oil. In *Proceedings of 37th Annual International Conference, Workshop and Exhibition of Chemical Society of Nigeria (CSN)* 2014, (Vol. 2, pp. 558-563).
26. Codex Alimentarius Commission (CAC) Graisses et huiles végétales, Division 11, Version abrégée FAO/ WHO. Codex Stan 1993, 20-1981, 23-198.
27. Vaitilingom, G. Utilisation des huiles végétales comme carburant des moteurs diesel, Revue Machinisme Agricole Tropical 1983, N° 82, p. 58-65.
28. Knothe G. Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel processing technology 2005, 86(10): 1059-1070
29. Santos, ME., Piovesan ND, Barros EG, Moreira MA. Low linolenic soybeans for biodiesel: Characteristics, performance and advantages, Fuel 2013, 104: 861-864
30. Ramos, M. J., Fernández, C. M., Casas, A., Rodríguez, L., & Pérez, Á. Influence of fatty acid composition of raw materials on biodiesel properties. *Bioresource technology* 2009, *100*(1), 261-268.
31. Rodríguez-Antón LM, Aparicio C, Guignon B, & Sanz PD. Volumetric properties at high pressure of waste oil methyl ester compared with diesel oil. Fuel 2008, 87(10-11) : 1934-1940
32. Prieto NMCT, Ferreira AGM, Portugal ATG, Moreira RJ, Santos JB. Correlation and prediction of biodiesel density for extended ranges of temperature and pressure. Fuel 2015;141:23–38.
33. Knothe G. Designer biodiesel: optimizing fatty ester composition to improve fuel properties. Energy & Fuels 2008, 22(2): 1358-1364.
34. Gouw TH, Vlugter JC, & Roelands CJA. Physical properties of fatty acid methyl esters. VI. Viscosity. Journal of the American Oil Chemists Society 1966, 43(7) 433-434.
35. Knothe G, & Steidley KR. Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. Fuel 2005, 84(9) : 1059-1065.

***** *****