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Research Article

Thermophysical Properties Derived from Density and Kinematic Viscosity Measurements of Blends of *Chrysophyllum albidum* Biodiesel and Pure Diesel Fuel

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Abstract

Binary blends of 5%, 10% and 20% biodiesel (Bd) derived from unconventional vegetable oil of *Chrysophyllum albidum* with pure diesel (Dp) were investigated in this study. The density of the binary blends was evaluated at pressures up to 40MPa and varying the temperature from 293.15K to 353.15K. Similarly, the kinematic viscosity of the samples was measured and presented in this work at atmospheric pressure in a temperature range from 293.15K to 373.15K. The density values were adjusted from the modified Tait-like equation with mean absolute deviations of about 0.005%. Density values were used to estimate the isothermal compressibility coefficient of the blends of biodiesel (Bd) with pure diesel (Dp). The density and kinematic viscosity of ethyl biodiesel are higher than those of the Bd/Dp blends and decrease with increasing temperature. The density and kinematic viscosity of the blends decrease with the proportion or amount of biodiesel in the Bd/Dp blends in the order B5 < B10 < B20. The isothermal compressibility of the samples increases with increasing temperature at constant pressure and decreases with increasing pressure along the isotherm. The absolute mean deviations between the measured densities and those calculated using the Tait-Like equation for our examined samples at around 0.005% confirm the accuracy of the modeling and the reliability of the calculated isothermal compressibility coefficient values.

Keywords

Blend, Biodiesel, Diesel, Density, Viscosity and Isothermal Compressibility

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1. Introduction

Biomass represents a renewable energy source whose use is growing exponentially in order to escape the devastating effects of fossil fuel exploitation [1]. Its exploitation makes use of different conversion technologies, such as thermochemical conversions, biochemical conversions and physicochemical conversions. They make it possible to obtain, among other things, biofuels, biofuel, coal briquettes, etc. Biofuels (vegetable oils, bioethanol, biodiesel, biogas) obtained from oleaginous biomass and animal fats, have the advantage of being available, renewable and biodegradable [2]. Thus, good control of the production of biofuels can constitute a credible energy alternative. As fuel, vegetable oils can be used in their pure state, mixed with petroleum diesel or as raw material for the production of biodiesel [3]. Indeed, many processes for converting vegetable oils are being developed to obtain a more efficient fuel, including biodiesel. Transesterification is one of the methods that seems to be promising. Methanol, a petroleum derivative, is generally used to synthesize fatty acid methyl esters from the triglycerides contained in vegetable oils [4]. Optimizing the transesterification reaction allows for a yield of over 98% in just a few minutes. However, using ethanol from plant biomass would not only produce quality biodiesel, but also improve the economic and environmental impact of the conversion [5].

The oilseed species of tropical regions are numerous and varied. More than 250 species of plants are used in tropical Africa for their oil. Most of these vegetable oils are extracted from harvested seeds. However, more than two-thirds of these species can be cultivated. This domestic production offers not only the possibility of increasing productivity, but also of adapting the species to local conditions and protecting them [6, 7]. The West African region is known as a producer of various edible oilseeds (cotton, palm, peanut, sesame, shea, etc.) or non-edible oilseeds (Neem, Jatropha curcas, Ricin, Balanites, Ceiba pentandra etc.). However, current local production is not sufficient to meet food, medicinal, industrial or energy needs.

The choice of vegetable oils for the production of biodiesel is multiple. The availability of the oilseed species at the local level as well as its oil yield, remain the first parameters that determine the possibilities of its long-term energy use [8]. Thus, like tropical plants such as ceiba pentandra [9], *Madhuca indica, Azadirachta indica, Jatropha curcas, Balanites aegyptiaca* [10] whose seeds produce inedible vegetable oils due to the presence of undesirable substances in their fatty acid profiles, Chrysophyllum albidum has long remained undervalued in Benin. The selection and valorization of this species results from the many advantages they offer, in particular their availability, their acclimatization, their resistance to drought and insect pests, their low need for fertilizers and their significant yield of vegetable oil [11]. Indeed, *chrysophyllum albidum* is a tropical evergreen tree belonging to the sapotaceae family. It is mainly a species of forest tree widely distributed in West, Central and East Africa that reaches average dimensions between 25 and 37 meters high with a circumference of maturity varying on average between 1.5 and 8 meters [12]. These fleshy fruits are popularly eaten and are a potential source of a soft drink. The fruits are also suitable for the production of fruit jams and jellies. Ecologically, the tree has an efficient nutrient cycle and the high mineralization rate of the leaves improves the superior quality of the soil. In Benin, *Chrysophyllum albidum* is a domestic tree and often found in villages especially in southern Benin. Thus the fruits of *Chrysophyllum albidum*, harvested during the months of November and April in homes and in some fields, are very early dumped in local markets to reach secondary markets by the know-how of several rural women and collectors of these markets. Unfortunately, despite the richness of this fruit, its production does not yet constitute a sector in Benin, due to a lack of organization of the sector. On the other hand, during the harvest period, a very large quantity of the fruit is destined for the trash. Barely 10% to 20% of the quantity of fruit is directly consumed [12]. Thus, it is essential to valorize these 80% to 90% of little or not exploited fruits rich in sugar and lignocellulose and triglycerides that are available, thanks to their bioconversion into biofuels (bioethanol and biodiesel) in the face of the many disadvantages associated with the use of fossil fuels and greenhouse emissions. Several studies have addressed the valorization of this plant species. Thus, in 2006, Idowu et al., also studied the potential use of seeds as a food ingredient [13]. In 2010, Chukwumalume et al. also showed that the seeds are a good source of vegetable oil [14]. Adepoju et al. (2012) determined the nutrient and micronutrient composition [15]. Regarding solvent extraction, several data from the literature have highlighted that the latter allows to provide the best yield of oil from the seeds of the plant, leaving a residue of less than 1% of vegetable oil [9]. In 2011, Ochigbo and Paiko showed the effect of solvent mixing on the characteristics of oils extracted from *Chrysophyllum albidum* seeds [16]. Furthermore, Kouwanou et *al.* (2018), evaluated the morphological and physicochemical properties of the fruits of *chrysophyllum albidum* from Benin for their use as raw material in the production of biofuel (Table 1) [12]. Furthermore, Montcho et *al.* (2022) evaluated chemical and thermophysical properties of vegetable oil from *Chrysophyllum albidum* seeds and derived ethyl biodiesel (Table 2) [17]. On the other hand, there is little or no work available in the literature on the characterization of the direct blend of biodiesel derived from *chrysophyllum albidum* seed oil with diesel.

In this study, unconventional vegetable oil of *chrysophyllum albidum* was converted into ethyl esters by the transesterification reaction under basic catalysis. The fatty acid profile of the oil was also determined. Density was measured with a vibrating tube technique for ethyl biodiesel from *chrysophyllum albidum* in a pressure range of 0.1 to 40 MPa

and kinematic viscosity at temperatures ranging from 293.15 to 353.15 K. Isothermal compressibility of biodiesel as well as biodiesel-diesel blends up to 40 MPa and from 293.15 K to 353.15 K was determined from density measurements. Density and compressibility are essential properties because injection systems, pumps and injectors must provide the precise amount of fuel to ensure proper combustion. Experimental density data were correlated using a Tait-Like equation, obtaining an excellent representation of the data set over the entire temperature and pressure range. The kinematic viscosity values of the different samples were corrected from the kinetic energy equation.

Table 1. *Vegetable oil extraction yield, quality indices and vegetable oil conversion of chrysophyllum albidum kernels to ethyl esters [5, 12, 17].*

Parameters Units		Values
Water and volatile matter content	(%) (m/m)	2.64± 0.08
Oil yield	(%) (m/m)	33.23 ± 3.26
Acid value	(mg KOH/g-Huile)	3.6 ± 0.23
Iodine value	(mg I_2/100 g-Huile)	33.21 ± 0.08
Peroxide value	(méq O_2/Kg-Huile)	10.46± 0.12
Free fatty acid [FFA] content	(%) (m/m)	0.16±0.02
Conversion rate	(%) (m/m)	96.20±0.34
Purification	(%) (m/m)	86.45±1.03
Biodiesel yield	(%) (m/m)	86.05±2.28

Table 2. *Fatty acid profile of vegetable oil from Chrysophyllum albidum kernels [17].*

Esters	(%)
Ethyl Myristate (C14:0)	2.28
Ethyl Palmitate (C16:0)	15.98
Ethyl Stearate (C18:0)	4.19
Ethyl Arachidate (C20:0)	2.26
Ethyl Behenate (C22:0)	0.82
Ethyl Eicosatrienoate (C23:0)	1.68
Ethyl Lignocerate (C24:0)	1.76
Ethyl Palmitoleate (C16:1)	1.99
Ethyl Oleate (C18:1)	19.7
Ethyl Gondoate (C20:1)	2.02
Ethyl Erucate (C22:1)	0.50
Ethyl Linoleate (C18:2)	21.22
Ethyl Linolenate (C18:3)	25.62

2. Materials and Methods

2.1. Preparation of Biodiesel from *Chrysophyllum albidum* Kernel Oils

Vegetable oil from *Chrysophyllum albidum* seeds was obtained by Soxhlet extraction using hexane at 69 ℃ under reduced pressure from ground dried almonds. The transesterification reactions were carried out in two steps. In the first step, the fatty acids of the vegetable oil were esterified by homogeneous acid catalysis using an ethanol: oil molar ratio of 30:1 in the presence of concentrated H_2SO_4 (1% m/m of oil) and moderate stirring (250 rpm at 78 ℃/1 hour). Then, the reaction was neutralized with 25% (m/m of oil) sodium bicarbonate solution for 5 min under slow stirring and the phases were separated in a separating funnel. The obtained ester was dried and then filtered with anhydrous sodium sulfate (Na_2SO_4). The residual solvent was evaporated under reduced pressure and the ester-rich phase was then weighed. The unreacted triglycerides and partial glycerides (mono and diglycerides) contained in the ester-rich phase were transesterified in a 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 of oil) and the temperature 60 ℃ for 2 hours under moderate stirring (250 rpm). The final mixture was separated in a separatory funnel and the ester-rich phase was dried with anhydrous sodium sulfate and filtered through filter paper.

2.2. Biodiesel-pure Diesel Blend (Bd/Dp)

Prepared biodiesel (Bd) was used to prepare the binary biodiesel-pure diesel blends. Thus, the blends were prepared at 20 ℃ in an Erlenmeyer flask with a lid at 250 rpm stirring for 10 min. In this study, Bd derived from *chrysophyllum albidum* seeds was blended with pure diesel (Dp) in three proportions namely 5%, 10% and 20% by volume of Bd to evaluate its properties. These blends were named B5, B10 and B20 respectively.

2.3. Density and Kinematic Viscosity Measurements

Density measurement

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 biodiesel and Bd/Dp blends (Figure 1). An additional DMA 512 cell was fitted to this device, which

allows pressure measurements up to 400 bars. In this study, the device 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 the vibration period to be measured with a certain precision. 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 PN 5207 thermometer with an uncertainty of 0.05 K. A volumetric piston pump is used to apply pressure to the system, the measurement of which was carried out by an HBM PE 200/2000 sensor with an uncertainty of 0.1%. Before and after each manipulation (sample loading), the densimeter and all capillaries are cleaned with petroleum ether and hexane to eliminate all traces of residues of the substance previously studied. 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. Dans ce type de dispositif, la masse volumique est liée à la période de vibration, par l'équation:

$$\rho(p,T) = A(p,T)\zeta^2(p,T) - B(p,T) \quad (1)$$

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

Regarding the calibration, we opted for the method used by Comuñas et *al.*, which is more suitable for our field of investigation [18]. It should be noted that this technique is based on the hypotheses made by Lagourette et *al.*, in 1992 [19].

Taking into account Lagourette's hypotheses and water as the reference substance, we can write the equation below:

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

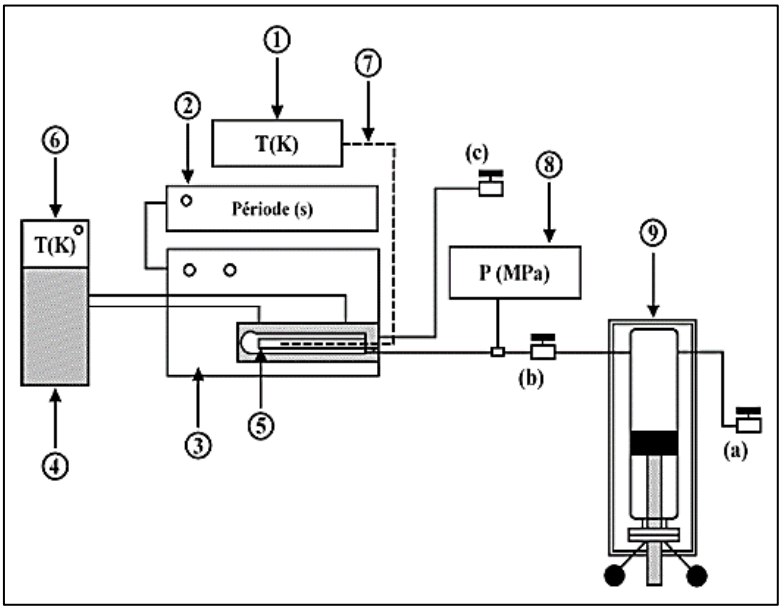

Figure 1. *Experimental density measuring device.*

The various representative parts of the density measuring device: ① Digital thermometer AOIP 5207; ② Frequency meter; ③ DMA 512; ④ Heat transfer fluid circulation bath; ⑤ Tuning fork; ⑥ JULABO thermostat; ⑦ Pt 100 probe; ⑧ Buffer cell; ⑨ HBM pressure gauge; ⑩ Piston pump; (a), (b), (c) Valves.

Measurement of kinematic viscosity

The kinematic viscosity of our samples was determined with a SCHOTT-GERÄTE Ubbelohde viscometer. A correction for the kinetic energy 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 suspended with its holder in a transparent thermostat from SCHOTT-GERÄTE. In order to avoid measurement errors of the viscometer, the temperature in the thermostat was kept constant at ±0.01 ℃. Each capillary tube is supplied with a calibration certificate, but the calibration of the capillary viscometer was checked at several temperatures using the "Viscosity Reference Standard" fluid S20 supplied by ColeParmer. The uncertainty is less than 1%.

3. Results and Discussion

Density

Table 3 lists the density values of Bd/Dp mixtures (B5, B10, B20) as a function of temperature and pressure.

Table 3. *Density measurement of Bd/Dp mixtures.*

Pressure (MPa)	Bio-diesel-diesel mixture	Temperature (K) 293.15	313.15	333.15	353.15
		Density (Kg/m^3)			
	B5				
0.1		837.47	823.77	808.49	794.14
10		843.49	828.27	816.09	802.50
20		849.31	835.76	822.81	810.02
30		854.55	841.79	829.14	816.58
40		859.56	847.24	835.05	823.33
	B10				
0.1		841.54	827.29	814.14	798.50
10		847.12	833.75	821.05	806.72
20		852.70	839.72	826.56	813.96
30		857.94	845.75	833.09	820.85
40		862.80	851.11	838.95	827.12
	B20				
0.1		848.66	835.45	823.78	806.31
10		854.63	841.72	828.12	814.49
20		860.36	847.79	835.08	821.43
30		865.60	853.73	841.23	828.48
40		870.32	859.09	846.75	834.84

Density is an important property for better combustion of fuel in the engine. Indeed, pumps and injectors are set to provide a volume, this volume must correspond to a precise quantity of material, therefore imposes a value on the density. Figure 1 shows the effect of temperature and pressure on the density of the mixtures (B5, B10 and B20) of Bd/Dp. We note a progressive decrease in density under the effect of temperature at constant pressure. On the other hand, it increases linearly with pressure at constant temperature. In short, the mass remains constant and the volume decreases, therefore the density increases as the temperature decreases. In 2022, Montcho et *al*., evaluated the density of biodiesel and binary mixtures with commercial *ceiba pentandra* vegetable oil diesel [20]. This study revealed the same behavior of density as a function of temperature and pressure. The same parameters were measured on *Chrysophyllum albidum* biodiesel by Montcho et *al.* in 2022 and as expected, the same density behavior is noted on the influence of temperature and pressure [17].

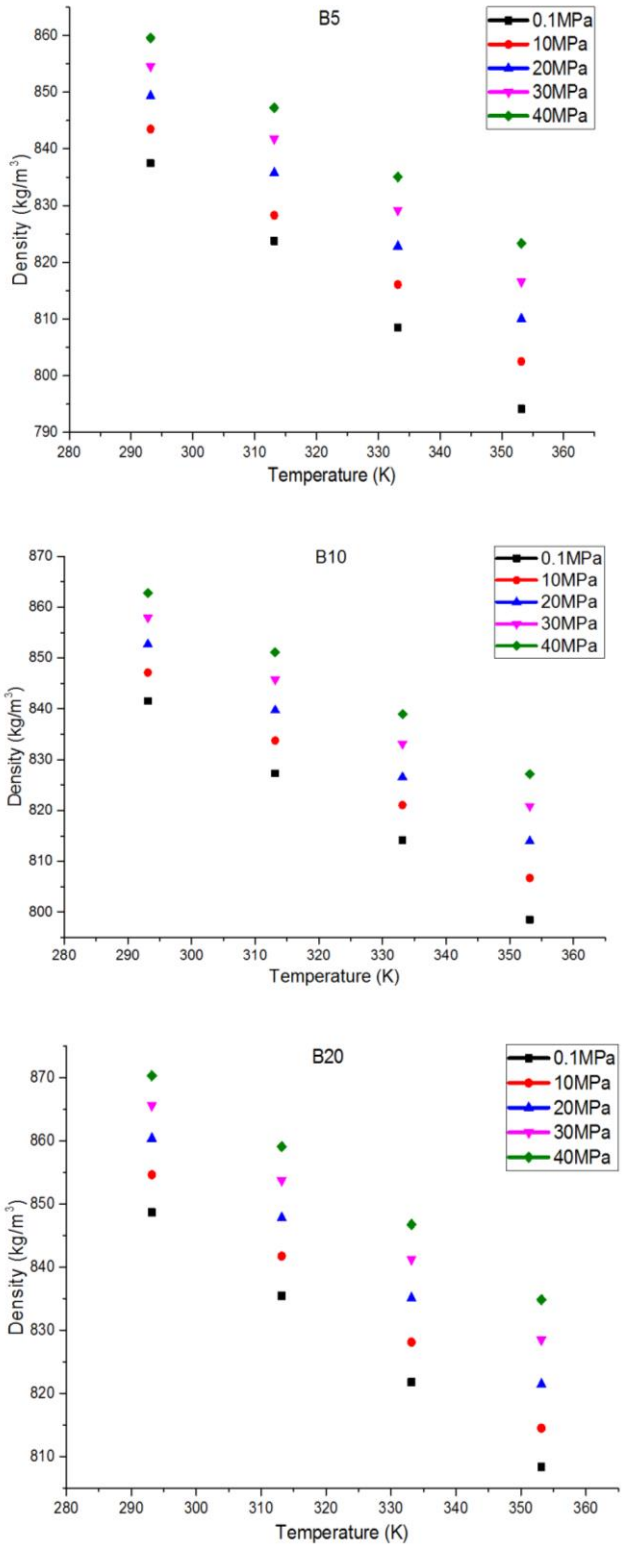

Figure 2. *Variation of density as a function of temperature at constant pressure.*

Kinematic viscosity

Kinematic viscosity is an important property that affects injector operation by decreasing injector pressure and making diesel atomization in the combustion chamber more difficult. The kinematic viscosity of different Bd/Dp blends made in proportions of 5%, 10% and 20% by volume of the corresponding biodiesel was evaluated as a function of temperature. The kinematic viscosity values are summarized in Table 4. As expected, a low kinematic viscosity value was observed as the temperature increased. Compared to unconventional vegetable oil-derived Bd, Bd/Dp blends (B5, B10 and B20) exhibited better kinematic viscosities. In 2022, Montcho et *al.*, evaluated the kinematic viscosity of biodiesel and binary blends with commercial *Ceiba pentandra* vegetable oil diesel. This work yielded similar results [20].

Table 4. *Kinematic viscosity of biodiesel and Bd/Dp blends.*

Biodiesel and blends	Temperature (K)			
	293.15	313.15	333.15	353.15
	Viscosity (mm^2/s)			
B100	10.36	6.4	3.58	2.75
B5	5.15	3.26	2.27	1.71
B10	6.85	4.22	2.87	2.11
B20	9.14	5.90	4.29	3.24

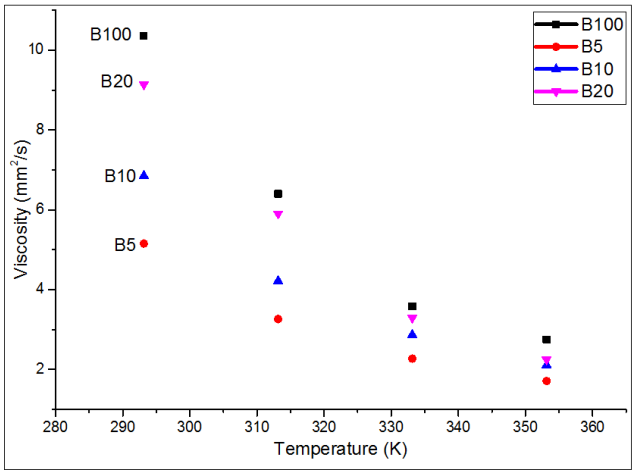

Figure 3. *Variation of the kinematic viscosity of the different mixtures as a function of temperature.*

The density values of different Bd/Dp mixtures varying the temperature (298.15 to 353.15) K and the pressure ranging from (0.1 to 40) MPa summarized in Table 3 were correlated from the TAIT-Like equation.

$$\rho(T,P) = \frac{\rho_0(T)}{1-\rho_0 A \ln\left(1+\left(\frac{P-P_0}{B(T)}\right)\right)} \quad (3)$$

With $\rho_0(T) = A_0 + A_1 T + A_2 T^2$ et $B(T) = B_0 + B_1 T + B_2 T^2$

The comparison of the experimental density values and those found with the TAIT-Like correlation was made using the mean absolute deviations (AAD), the maximum deviation (DMax) and the mean deviation (Bias). These parameters AAD, DMax and Bias were determined from the equations defined below [21]:

$$AAD = \frac{100}{N} \sum_{i=1}^{100} \left| \frac{\rho_i^{exp} - \rho_i^{calc}}{\rho_i^{exp}} \right|; \quad (4)$$

$$DMax = Max\left(100 \left| \frac{\rho_i^{exp} - \rho_i^{calc}}{\rho_i^{exp}} \right|\right) \quad (5)$$

$$Bias = \frac{100}{N} \sum_{i=i}^{N} \frac{\rho_i^{exp} - \rho_i^{calc}}{\rho_i^{exp}} \quad (6)$$

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

The parameters of the TAIT-Like equation as well as the AAD, DMax and Bias determined with the density correlation are grouped in Table 5.

Table 5. *Parameters and deviation obtained from the TAIT-Like equation.*

Coefficients	B5	B10	B20
A_0 ($g.cm^{-3}$)	1.6236	-0.0904	2.0053
A_1 ($g.cm^{-3}.K^{-1}$)	-0.0053	0.0097	-0.0094
A_2 ($g.cm^{-3}.K^{-2}$)	1.4179×10^{-6}	-3.1653×10^{-5}	2.6691×10^{-5}
ρ_0 ($g.cm^{-3}$) à 293,15K	0.8379	0.8403	0.8485
A (MPa)	-0.0825	-0.0950	-0.1028
B (MPa)	89.6024	102.0001	123.1022
AAD (%)	0.0065	0.0057	0.0057
DMax (%)	0.0112	0.0116	0.0107
Bias (%)	-0.0064	-0.0057	-0.0057

The mean absolute deviations (AAD) between the measured density values and those calculated using equation (3) are equal to 0.0057% for the Bd/Dp mixtures, thus showing the good quality of the density modeling.

Isothermal compressibility

The isothermal compressibility coefficient is one of the important properties for understanding the thermodynamic

behavior of fluids in engines. Furthermore, it is one of the properties to consider when selecting a hydraulic fluid for a particular application. Indeed, low compressibility results in fast response time, high pressure transmission speed, and low power loss. In hydraulic systems operating at high pressure, oils with low compressibility are required to transmit power efficiently. Based on the density measurement results of the formulated biodiesel and Bd/Dp blends presented above, we were able to calculate the isothermal compressibility χ_T as a function of pressure (0.1–40 MPa) in the temperature range (298.15–353.15 K) using the parameters of the TAIT-Like equation (Table 5).

$$\chi_T = \left(\frac{1}{\rho}\right)\left(\frac{\partial \rho}{\partial P}\right)_T \quad (7)$$

The product of the inverse of the density (3) and its derivative with respect to the pressure at constant temperature allows us to write:

$$\chi_T = \frac{A\rho_0(T)}{(B+p-0.1\ \text{MPa})\left[1+A\rho_0 \ln\left(1+\frac{p-0.1\ \text{MPa}}{B}\right)\right]} \quad (8)$$

The values of the isothermal compressibility coefficient (χ_T) of the Bd/Dp mixtures are grouped in Table 6.

Table 6. *Measurement of isothermal compressibility of biodiesel and Bd/Dp blends as a function of temperature and pressure.*

P/MPa	Biodiesel and Blends	T/K 293.15	313.15	333.15	353.15
		10^3 k_T/MPa^1			
	B5				
0,1		0.775	0.828	0.983	1.116
10		0.703	0.753	0.881	0.992
20		0.644	0.690	0.798	0.892
30		0.594	0.637	0.730	0.812
40		0.552	0.592	0.673	0.745
	B10				
0,1		0.688	0.828	0.882	1.097
10		0.658	0.762	0.801	0.969
20		0.631	0.706	0.733	0.867
30		0.606	0.658	0.676	0.786
40		0.583	0.616	0.628	0.719
	B20				
0,1		0.756	0.830	0.910	1.036
10		0.686	0.753	0.806	0.942
20		0.628	0.689	0.723	0.863
30		0.578	0.636	0.656	0.798
40		0.537	0.590	0.600	0.742

Figure 4 presents the graphs of the variation of the compressibility coefficient of the three Bd/Dp blends as a function of the pressure at 333.15 K. From the values presented in this table and the graphs (Figure 4), it can be seen that the isothermal compressibility decreases as a function of the pressure for the three blends B5, B10 and B20 and increases with the temperature at constant pressure. In addition, the lowest variation of the isothermal compressibility coefficient as a function of the pressure is associated with the B20 blend while the greatest variation corresponds to the B5 blend. In short, the comparison of the variation of the isothermal compressibility coefficients as a function of the pressure of these blends at 333.15 K gives an idea of the nature and volume of biodiesels during the preparation of the Bd/Dp blends.

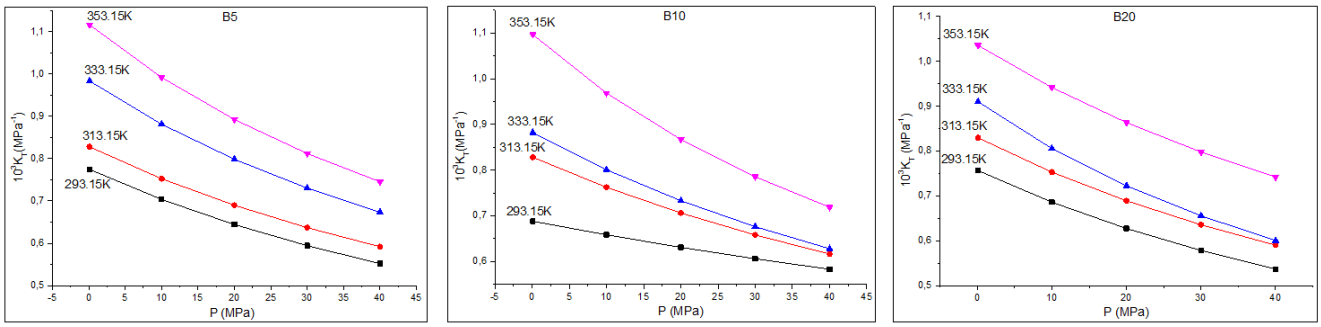

Figure 4. *Variation of the compressibility coefficient (χT) as a function of the pressure of the Bd/Dp mixtures.*

Some thermophysical properties and fuels

Pure diesel (Dp) was used to improve the behavior of biodiesels in the diesel engine. Thus, binary blends in the proportions of 5%, 10% and 20% by volume of biodiesel are prepared to evaluate their thermophysical and fuel properties. The results of these properties are summarized in Table 7. It is clear from the analysis of this table that the density and kinematic viscosity values are all lower than those of the formulated biodiesel. Better, our density and viscosity values of the Bd/Dp blends are well below the limit values recommended by biodiesel standards such as ASTM (American Society for Testing and Materials) D6751 [22] and the European standard EN 14214 [23].

Table 7. *Physical and fuel properties of Bd/Dp blends [24].*

Properties of mixtures	Density (Kg/m^3)		Kinematic viscosity (mm2/s) à 40°C	Dynamic viscosity (µPa.s) 40°C; 0,1MPa
	20°C; 0,1 MPa	40°C; 0,1 MPa		
B5	837.47	823.77	3.26	2.69
B10	841.54	827.29	4.22	3.49
B20	848.66	835.45	5.90	4.93
Diesel	-	-	4.2	-
Norme ASTM D6751	-	880	1,6_6,0 à 40°C	-
Norme EN 14214	-	860-900 à 15°C	3.5-5,0 à 40°C	-

Srithar et *al*. (2014) observed a remarkable change in the physicochemical properties of biodiesel-diesel blends [25]. In fact, they found that the mixture of 90% diesel, 5% Pongamia pinnata biodiesel and 5% mustard oil biodiesel offers an improvement in the density and kinematic viscosity values compared to the values recorded for the corresponding biodiesels [25]. Furthermore, Sanjid et *al.* (2016) also obtained similar results for blends of Ceiba pentandra and Moringa oleifera biodiesels with petroleum diesel. They found that blending the biodiesels (5% C. pentandra and 5% M. oleifera) resulted in low density and kinematic viscosity values compared to 10% blends made under the same conditions [26]. Bd/Dp blends have better fuel properties and are in accordance with biodiesel standards (ASTM and EN 14214) [22, 23]. In general, it appears that the addition of Bd formulated in Dp at different proportions modifies the physicochemical and fuel properties of the biofuel and consequently the engine performance.

4. Conclusions

This study is of great interest in the field of biofuels in order to generate a database of thermophysical and fuel properties to contribute to the improvement of diesel engine performance as well as the behavior of Bd/Dp blends in engines. The density and isothermal compressibility were evaluated for a range of temperatures (293.15 K to 353.15 K) and pressures up to 40 MPa. The kinematic viscosity was determined at atmospheric pressure by varying the temperature from 293.15 to 353.15K. This study showed that the density and kinematic viscosity of Bd/Dp blends decrease with increasing temperature. On the other hand, they increase with increasing the amount of Bd in each of the blends. The density and kinematic viscosity estimation allowed to identify the Bd/Dp blends that meet the ASTM D6751 and EN 14214 standards for their use in diesel engines as substitutes for crude Bd and then for commercial Dp. From the density measurements, the isothermal compressibility coefficient was determined for each of the synthezed biodiesel-diesel blends. The B5 blend gives satisfactory values comparable to that of Dp. We also noted that the isothermal compressibility coefficient of the studied Bd/Dp blends increases with temperature at constant pressure. The estimation of the density, kinematic viscosity and the isothermal compressibility coefficient in extended temperature and pressure ranges will be useful for other industrial applications and the development of high-power diesel engines. In summary, the results presented in this study can be used to reassure and give confidence to users on the use of Bd/Dp mixtures in diesel engines. Looking ahead, we plan to characterise other types of blends (blends of two or three biodiesels with petroleum diesel, blends of vegetable oil, biodiesel and fossil diesel) with a view to their transferability to diesel engines. In addition, we plan to continue our research into the study of engine performance with each of the biodiesels and bio-

diesel-diesel blends.

Abbreviations

AG	Fatty Acids
BECa	*Chrysophyllum albidum* Ethyl Biodiesel
BEL	Liquid Biomass
Ca	*Chrysophyllum albidum*
CPG	Gas Chromatography
Bd	Biodiesel
Dp	Diesel
EEHV	Ethyl Esters of Vegetable Oils
EMG	Methyl Esters of Fatty Acids
ETBE	Ethyl- TertioButyl-Ether GES Greenhouse Gases
IFP	Institut Français du Pétrole
OPEC	Organisation of Petroleum Exporting Countries
EU	European Union

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Papin Sourou MONTCHO, Guevara NONVIHO, Assou SIDOHOUNDE, Cokou Pascal AGBANGNAN DOSSA, David BESSIERES, Anna CHROTOWSKA et Dominique C. K. SOHOUNHLOUE Wrote the first draft of the manuscript. All authors commented.

Conflicts of Interest

The authors declare no conflicts of interest.

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