Temperature dependence of density and viscosity of vegetable oils

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ABSTRACT

The straight use of vegetable oils as fuel in diesel engines entails adjusting several physical properties such as density and viscosity. By adequately heating the vegetable oil before entering the injection system, its physical parameters can reach values very close to that of diesel fuel. Consequently, by properly adjusting the temperature of vegetable oils used as fuel, it is possible to improve their combustion performance, thus avoiding premature engine aging due to incomplete burning. In this study the density and viscosity of several vegetable oils are studied within a wide variety of temperatures. The optimal range of temperatures at which each vegetable oil should operate in order to adjust its properties to those of automotive diesel and biodiesel is then found. Additionally an empirical relationship between the dependence of viscosity with density is presented. Thus, by means of the above-described relationship, through measuring the density of a given oil, its viscosity can be directly deduced.

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1. Introduction

Diesel engines are being extensively utilized worldwide due to their high economic advantage and durability [1,2]. They have appealing features including robustness, high torque, and lower fuel consumption under certain conditions. According to Moron et al. [3] they are prevalent in sectors such as road and train transport, agriculture, military, construction, mining, maritime propulsion and stationary electricity production. Diesel engines can use several fuel types, including diesel fuel, straight vegetable oils (SVO), biodiesel — transesterified vegetable oil — and short chain alcohols. Diesel engines may also function with hybrid fuels, including SVO mixtures in different proportions with diesel or diesel/ethanol.

At the present time there is an increasing demand for energy, concerns about global warming and a growing interest in renewable energy sources; particularly in biofuels [4,5]. This is due to diminishing reserves and price instability of the world's petroleum fuel. These challenges are in part due to the diesel engines themselves. Consequently, it is an urgent matter to reduce hazardous pollutants that diesel engines emit such as NO_x, CO, CO_2 and particulate matter (PM). According to Lee at al. [1] this can be achieved by using new combustion technology, by improving fuel characteristics and or by applying after-treatment technology. It is well known that utilizing biofuels with internal combustion engines may contribute to reduce greenhouse gas emissions [6]. Small-scale produced SVOs are considered attractive options for renewable fuel because of environmental benefits [7]. Small-scale use of vegetable oils is also considered an interesting option because they can be obtained from agricultural or industrial sources with very simple processing. This processing includes cold pressing and refining stages that avoid

chemicals and complex processes involved in biodiesel production. To summarize, the straight use of vegetable oils in diesel engines avoids the transesterification stage required to obtain biodiesel, lowering energy consumption and reducing considerably environmental impacts due to lower polluting emissions and less chemicals consumption [7].

There are some similarities between most available vegetable oils and diesel fuel, making the vegetable oils appealing to be used as fuel. For example, the lower heating values (LHVs) of vegetable oils are very close to that of diesel fuel [8]. However, some physical and chemical differences exist. For example, the cetane number is a variable that affects the ignition quality and therefore determines the flammability of the fuel [9]. Diesel fuel has higher cetane number than vegetable oils, implying a shorter ignition delay [10] and a small change in engine efficiency [11]. However, the difference in ignition delay between diesel fuel and SVOs is not significant [9] and may be compensated by adjusting the ignition delay [12]. It is an accepted fact that viscosity has a significant effect on spray characteristics. Higher viscosity leads to: inferior fuel atomization, higher Sauter mean diameter —the ratio of the mean volume to the mean surface of the fuel droplets— and lower spray speed than conventional diesel fuel [13–16]. The atomization effectiveness depends on the geometry of the injection system, various fuel properties such as viscosity, surface tension and density [3,17]. SVO viscosity has a profound effect on the flow through the fuel system, thus influencing how the oil sprays from the injector.

It is also an accepted fact that the large molecular sizes of the triglycerides contained in vegetable oils results in higher viscosity, higher density and lower volatility compared to diesel fuel. That, in turn, causes poor fuel atomization due in part to the large size of droplets upon injection into the cylinder and also due to high-spray jet penetration. Optimal atomization improves mixing and complete combustion in diesel engines, which has great impact on emissions and efficiency [18]. Higher viscosity fuels cause the jet to become a solid steam instead of a spray composed of small droplets [19] resulting in poor combustion that produces black smoke and provokes the development of deposits in the combustion chamber. Furthermore, the introduction of unburnt fuel, which flows down the cylinder wall into the crankcase, dilutes the vegetable oil in the lubrication engine oil [20]. Higher viscous fuels tend to form larger droplet size, which fosters other competitive reactions, such as charring or coking and polymerization. Contrarily, as pointed out by Nwafor et al. [20], viscous fuels have a higher lubricating effectiveness. It is recognized that indirect injection engines are less affected by viscosity differences than direct injection engines [21,22].

Observations gathered using SVO as fuel in unmodified diesel engines draw attention to the need to fit the most relevant physical properties, which narrows this study to density and viscosity [23]. When using SVO as fuel in an unmodified diesel engine, its viscosity has to be lowered to allow appropriate atomization. If not, incomplete SVO combustion and carbonization will eventually damage the engine. Consequently, when using SVO in these engines, some precautions must be taken. Often, vegetable oils are preheated to reach appropriate density and viscosity values before reaching the injectors by using a heater. Once heated,

SVO becomes very similar to diesel fuel in terms of physical properties, which will be discussed further in this study.

Several studies have been carried out that focus on lowering the viscosity of vegetable oils by appropriate heating. One of the earliest studies was carried out by Murayama et al. [24] who suggested increasing the temperature of rapeseed oil to 200 °C to achieve efficient combustion for direct injection diesel engines. More recently, Agarwal et al. [25] found that heating the Jatropha oil between 90 °C and 100 °C before combustion in a diesel engine was adequate to lower the viscosity within a close range to diesel. Moreover this study concluded that preheating the Jatropha oil does not lead to change in optimum fuel injection pressure. Additionally, some of the available commercial kits applied to use SVO in automotive diesel engines utilize a heat exchanger to raise the temperature of vegetable oil. These kits frequently use the water of the cooling circuit to heat the SVO up to about 70–80 °C. All of this information makes it clear that there is discrepancy in the data concerning the optimal temperature at which each particular SVO should be preheated in order to obtain improved combustion.

Although density and even more so viscosity play an important role in the evaluation of fuel performance, there is very little published information about the optimal temperature level at which the SVOs have improved performance in diesel engines. Hence, it would be extremely beneficial to know the values of these properties within the vast range of temperatures to find out the most appropriate heating temperature for each one of the analyzed vegetable oils.

The aim of this paper is to obtain insightful knowledge about the temperature dependencies of the critical physical parameters, such as density and viscosity of commonly used vegetable oils, including rapeseed, sunflower, soybean, palm, corn and grapeseed. This includes the most significant vegetable oils produced worldwide during 2009, i.e. palm, soybean, rapeseed and sunflower [26]. The results presented in this study will allow adjusting the density and viscosity values of the vegetable oils with that of other fuels currently being used in diesel engines. Mathematical expressions of temperature dependences of these physical parameters are given to characterize the vegetable oils studied. Additionally, the densities and viscosities of the vegetable oils analyzed are compared with those of commercial pure biodiesel and automotive diesel fuel in order to compare their physical parameters. From this comparison and from the limit values proposed in Section 2.2, the heating temperature to match the density and viscosity values of automotive diesel and biodiesel is obtained.

In order to characterize the vegetable oils and pure biodiesel samples used in this study, their composition has been analyzed by means of gas chromatography. Table 1 gives a listing of the samples analyzed in this paper. Their fatty acid composition is given in mass percent.

2. Methodology

2.1. Temperature dependence of density and viscosity

As discussed in the introduction, density and viscosity play an important role in the atomization process, which in turn

Table 1 – Fatty acid composition of the analyzed vegetable oils.

Carbon number	Systematic name (common)	Rapeseed	Sunflower	Soybean	Palm	Corn	Grapeseed	Biodiesel
C12:0	Dodecanoic (lauric)	–	–	–	0.1%	–	–	–
C14:0	Tetradecanoic (myristic	<0.1%	<0.1%	<0.1%	0.9%	<0.1%	<0.1%	0.3%
C16:0	Hexadecanoic (palmitic)	4.7%	6.7%	11.2%	45.6%	11.4%	7.2%	18.6%
C16:1	Hexadecenoic (palmitoleic)	0.3%	0.3%	0.2%	0.4%	0.3%	0.1%	0.8%
C18:0	Octadecanoic (estearic)	1.3%	2.9%	2.9%	3.8%	1.7%	3.9%	4.5%
C18:1	Octadecenoic (oleic)	65.3%	38.7%	25.2%	38.5%	32.8%	20.2%	32.0%
C18:2	Octadecadienoic (linoleic)	19.2%	51.3%	55.4%	10.5%	53.3%	68.4%	39.7%
C18:3	Octadecatrienoic (linolenic)	8.3%	<0.1%	5.0%	0.1%	0.5%	0.2%	4.0%
C20:1	Eicosenoic (gadoleic)	0.7%	<0.1%	0.1%	–	<0.1%	<0.1%	–
C22:1	Docosenoic (erucic)	<0.3%	–	–	–	–	–	–

determines if complete combustion is carried out in a diesel engine which consequently influences engine emissions and efficiency. Therefore, in order to achieve the correct fuel atomization, proper values of density and viscosity are required. Moreover, both, density and viscosity are highly temperature sensitive. In this section these dependences are analyzed and mathematical equations to set them are explained.

2.1.1. Density

Density is an important physical characteristic of any substance, and is a measure of the mass per unit of volume of that substance. It is an accepted fact that vegetable oil density decreases linearly with increasing temperature. This relationship can be expressed mathematically as [27],

$$\rho = a + b \cdot T \tag{1}$$

where ρ is the density expressed in g cm^{-3}, T is the temperature expressed in °C, a is the intercept and b is a negative slope.

2.1.2. Viscosity

Viscosity is a measure of the resistance offered by a fluid to flow. According to Krisnangkura et al. [28] viscosity may be considered the integral of the interaction forces of molecules. When heat is applied to fluids, molecules can then slide over each other more easily making the liquid to become less viscous. The effect of temperature on the kinematic viscosity of liquid is described by means of the Arrenhius equation as,

$$\eta = A_1 \cdot \exp^{\frac{E_a}{RT}} \tag{2}$$

η being the kinematic viscosity, E_a the activation energy for flow, R the universal gas constant and T the absolute temperature. Additionally, $A_1 = N_A h/V$, where N_A, V and h are the Avogadro's number, the molecular volume and the Plank's constants, respectively. The SI physical unit of kinematic viscosity is m^2 s^{-1}.

In the case of vegetable oils, Equation (2) can be rewritten as in Equation (3) which is known as the Andrade equation [27,28]

$$\eta = A_1 \cdot \exp^{B/T} \tag{3}$$

where T is the absolute temperature and A_1 and B are specific constants to be adjusted for each specific oil. By applying logarithms to both sides of Equation (3) it leads to,

$$\ln(\eta) = A + B/T \tag{4}$$

Equation (4) allows us to linearize the Equation (3) by applying the least-squares method and making 1/T the independent variable. Additionally, Azian et al. [29] suggested modifying the Equation (4), which is especially useful when dealing with wide temperature ranges,

$$\ln(\eta) = A + B/T + C/T^2 \tag{5}$$

Sometimes, the dynamic or absolute viscosity μ is applied, which can be calculated from the kinematic viscosity η and the density ρ as,

$$\mu = \eta \cdot \rho \tag{6}$$

The SI physical unit of dynamic viscosity is the Pa s, which is identical to kg m^{-1} s^{-1}.

2.1.3. Interdependence between viscosity and density

As both, density and viscosity are highly temperature sensitive, it is possible to find out the dependence between them. This dependence is often used in the oil industry [30]. The measurement of density is very simple and quick because it requires a low-cost hydrometer that is quite easy to use. On the other hand, the measurement of the viscosity is more complex and time consuming, requiring a more complex and expensive assessment instrument employed by qualified laboratory technicians. If the relationship between density and viscosity is known, one only needs to measure the density of a given oil to deduce its viscosity. According to Rodenbush et al. [27], when dealing with vegetable oils the dependence between density and viscosity can be expressed as illustrated in Equation (7).

$$\rho = D + E/\eta^{1/2} \tag{7}$$

Equation (7) is particularly useful because it can be adjusted by means of a least-squares linear regression by choosing $1/\eta^{1/2}$ as an independent variable.

Table 2 – European standards related to automotive diesel fuel, biodiesel and rapeseed oil.

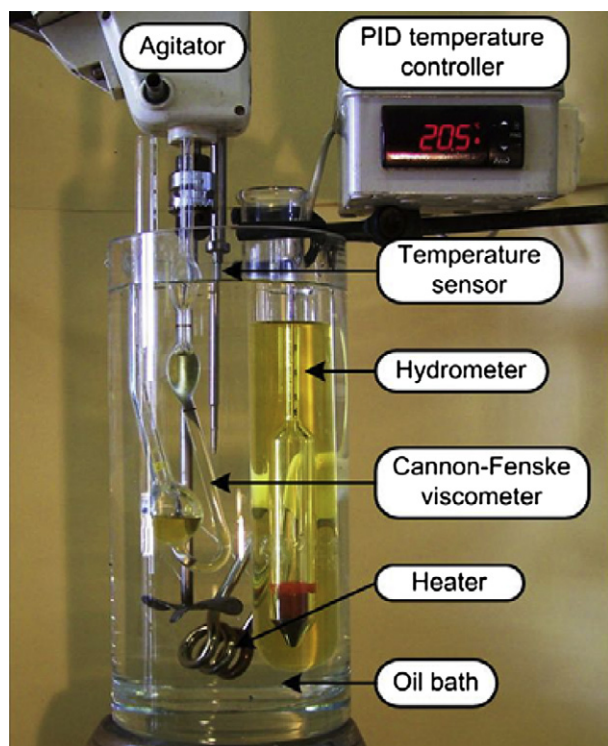| Standard	Fuel	Density (g cm^{-3})	Viscosity (mm^2 s^{-1})
		15 °C	40 °C
EN 590	Diesel fuel	0.820–0.845	2.00–4.50
EN 14214	Biodiesel	0.860–0.900	3.50–5.00
DIN 51605	Rapeseed oil	0.910–0.925	Max. 36.00

Fig. 1 – Experimental setup used to measure the density and viscosity of vegetable oils in the temperature range 10 °C–140 °C.

included in this comparison. Table 2 summarizes the limit values of density and viscosity for diesel fuel, pure biodiesel and rapeseed oil agreed upon by these European standards.

Concerning the performance of diesel engines, it is acknowledged that the effects of using vegetable oils greatly depend on the engine sensitivity to fuel injection and on the combustion characteristics of the vegetable oil [34,35]. Current diesel engines have fuel injection systems that are susceptible to viscosity changes [36]. According to Totten et al. [19], the recommended viscosity values for diesel engine fuels range from 1.8 to 5.8 mm^2 s^{-1} at 38 °C. The lower viscosity limit is imposed to provide adequate lubrication for injection system components and to prevent leakage. More recently, Mohamed Y.E. Selim [18] recommended a range lying between 1.6 and 7 mm^2 s^{-1} when operating at 40 °C. Thus, viscosity limit values imposed by EN 590:2004 and EN 14214:2009 [31,32] are compatible with viscosity values close to 5.8 mm^2 s^{-1}. This value is recommended in [19], and the range 1.6–7 mm^2 s^{-1} is suggested in [18]. Consequently, as deduced from technical literature, viscosity of vegetable oils should be lowered at least to values close to 6 mm^2 s^{-1} when used as fuel in diesel engines to match the values of the European standards, thus avoiding the problems related to higher viscosity fuels. Additionally, from the abovementioned standards a conservative density value for SVO of 0.860 g cm^{-3} is proposed as a ceiling value because it meets the well accepted EN 14214:2008 [32] standard for biodiesel.

2.2. Density and viscosity ceiling values

In this section different European standards regarding the density and viscosity requirements of various automotive fuels sold in the European Union are examined. The European standards analyzed are EN 590:2004 [31] which pertains to automotive diesel fuel and EN 14214:2008 [32] that is associated with biodiesel. The German norm DIN 51605 [33] concerning the straight use of rapeseed oil in diesel engines is also

3. Experimental

In this study samples of different types of refined vegetable oils were analyzed including rapeseed, sunflower, soybean, palm, corn and grapeseed. Pure commercial biodiesel (BD100) and automotive diesel fuel were also included in the sampling. The vegetable oils samples were purchased from different local suppliers, whereas the biodiesel and automotive diesel samples were acquired from local petrol stations.

Table 3 – Dependence of density with temperature for automotive diesel fuel, pure biodiesel and the analyzed vegetable oils. SVO density values below 0.860 g cm^{-3} are in bold.

Temp. (°C)	Density (g cm^{-3})							
	Diesel	BD100	Rapeseed	Sunflower	Soybean	Palm	Corn	Grapeseed
10	0.8376	0.8859	0.9210	0.9251	0.9254	–	0.9237	0.9259
20	0.8308	0.8798	0.9145	0.9169	0.9185	–	0.9167	0.9188
30	0.8242	0.8717	0.9080	0.9114	0.9127	–	0.9113	0.9126
40	0.8181	0.8641	0.9027	0.9043	0.9061	0.8996	0.9046	0.9060
50	0.8114	0.8583	0.8963	0.8994	0.8998	0.8922	0.8979	0.8998
60	0.8043	0.8513	0.8911	0.8926	0.8941	0.8845	0.8920	0.8941
70	0.7970	0.8433	0.8848	0.8877	0.8879	0.8789	0.8864	0.8874
80	0.7890	0.8372	0.8777	0.8798	0.8817	0.8721	0.8801	0.8813
90	0.7825	0.8287	0.8724	0.8743	0.8750	0.8664	0.8740	0.8754
100	0.7759	0.8229	0.8658	0.8670	0.8689	**0.8595**	0.8678	0.8695
110	0.7708	0.8150	**0.8593**	0.8602	0.8626	**0.8536**	0.8610	0.8626
120	0.7636	0.8075	**0.8537**	**0.8536**	**0.8566**	**0.8457**	**0.8555**	**0.8570**
130	0.7577	0.8002	**0.8469**	**0.8472**	**0.8498**	**0.8407**	**0.8489**	**0.8505**
140	0.7516	0.7912	**0.8395**	**0.8408**	**0.8430**	**0.8325**	**0.8424**	**0.8440**

Table 4 − Main parameters of the density−temperature fit.

Sample	a	b ($\times 10^{-4}$)	r^2	F_{calc} ($\times 10^4$)	F_{tab}
Diesel fuel	0.8442	−6.7009	0.99911	1.3466	4.7472
Biodiesel	0.8938	−7.2073	0.99932	1.7554	4.7472
Rapeseed	0.9273	−6.1837	0.99945	2.1884	4.7472
Sunflower	0.9310	−6.4145	0.99920	1.4907	4.7472
Soybean	0.9315	−6.2790	0.99985	8.0160	4.7472
Palm[a]	0.9250	−6.5612	0.99900	9.0182	5.1174
Corn	0.9295	−6.2053	0.99983	6.9725	4.7472
Grapeseed	0.9314	−6.2343	0.99982	6.7749	4.7472

a Analysis done for $T \geq 40$ °C, as palm oil is solid below 40 °C.

A set of calibrated hydrometers with spans ranging from 0.7 to 0.95 g cm^{-3} were used to measure the density. The thermal expansion of glass has a slight influence on the hydrometer reading. To compensate this effect the temperature correction according to the standard ISO 649-2:1981 [37] has been applied.

Additionally, three Cannon-Fenske-type gravity flow viscometers series 50, 100 and 150 were utilized to measure the viscosity. They allowed measuring viscosity of all of the analyzed oils and fuels with flow times within the recommended range set by the standard ISO 3105:1994 [38]. The viscometers were calibrated by the manufacturer and the calibration constant $C_0(T)$ is supplied with the instrument. The viscosity is obtained from the following equation,

$$\eta_{app} = t \cdot C_0(T) \qquad (8)$$

η being the kinematic viscosity in centistokes, t the flow time expressed in seconds and $C_0(T)$ the characteristic calibration constant of each viscometer measured at the working temperature.

Additionally, to ensure precise and stable temperature control during measurements, a resistance temperature detector (RTD) was used to measure the temperature. The RTD was connected to a digital temperature PID controller. The controller allowed regulating the temperature of a heated oil bath containing the hydrometer and the viscometer by means of an electric heater. The temperature of the oil bath was adjusted from 10 °C to 140 °C. Both, density and viscosity were measured within this temperature interval. Furthermore, the interdependence between density and viscosity was studied.

Each sample was tested three times, and the average density and viscosity were calculated. Fig. 1 shows the experimental setup used to determine the temperature dependence of density and viscosity of the samples analyzed.

3.1. Density

As stated, it is an accepted fact that fuel density has a great influence on the atomization process. Thus the knowledge of the temperature dependence of this parameter is a highly important component of the process of the study in order to ensure optimal combustion of the fuel [18].

The density of the different vegetable oils, pure biodiesel (BD100) and automotive diesel fuel samples were measured according to the method explained in Section 2.1.1. The set of measures carried out with in the range between 10 °C and 140 °C is shown in Table 3.

Results presented in Table 3 clearly show that the density of diesel fuel is much lower than the density of the vegetable oils studied. However, heating any of the vegetable oils at a temperature of 120 °C or higher is sufficient to ensure that density is below 0.860 g cm^{-3}, corresponding to the inferior density limit given by the EN 14214:2008 European standard [32] for biodiesel fuel in diesel engines. Despite these observations, this temperature requirement can be lower depending on engine types and configurations. For example, in engines used in applications such as combined heat and power (CHP), vegetable oil may be injected at lower temperatures [39].

Table 4 shows a summary of the most relevant parameters related to the density−temperature fit obtained by applying Equation (1) when analyzing the whole set of samples. Once

Table 5 − Dependence of kinematic viscosity with temperature for automotive diesel fuel, pure biodiesel and the analyzed vegetable oils. SVO viscosity values below 6 mm^2 s^{-1} are in bold.

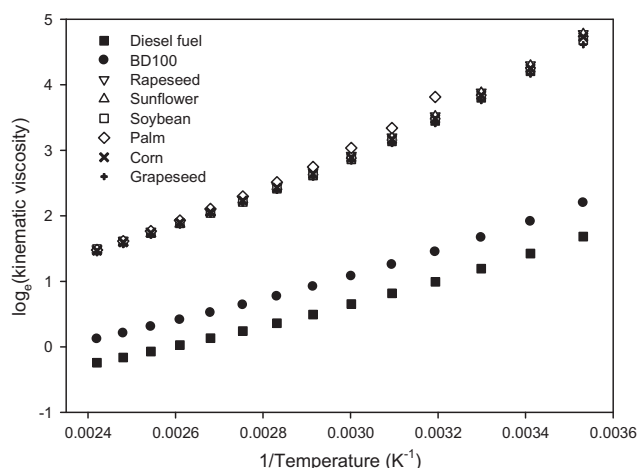| Temp. (°C)	Kinematic viscosity (mm^2 s^{-1})							
	Diesel	BD100	Rapeseed	Sunflower	Soybean	Palm	Corn	Grapeseed
10	5.39	9.00	119.48	118.72	107.62	−	113.39	100.63
20	4.15	6.78	74.19	73.45	67.12	−	70.29	64.32
30	3.30	5.30	48.88	48.46	44.69	−	46.54	42.94
40	2.70	4.26	34.06	33.78	31.42	45.34	32.53	30.19
50	2.26	3.51	24.68	24.48	23.00	28.19	23.74	22.29
60	1.92	2.94	18.62	18.52	17.47	20.84	17.96	17.04
70	1.64	2.51	14.48	14.44	13.67	15.60	14.01	13.34
80	1.43	2.16	11.58	11.53	11.17	12.35	11.39	10.88
90	1.27	1.90	9.45	9.44	9.13	9.94	9.34	8.96
100	1.14	1.69	7.89	7.78	7.71	8.21	7.83	7.53
110	1.03	1.51	6.70	6.50	6.58	6.88	6.65	6.42
120	0.93	1.36	**5.86**	**5.62**	**5.68**	**5.85**	**5.70**	**5.49**
130	0.85	1.23	**5.09**	**4.91**	**4.99**	**5.02**	**4.93**	**4.77**
140	0.78	1.13	**4.47**	**4.37**	**4.45**	**4.38**	**4.34**	**4.21**

Fig. 2 — Dependence of $\log_e$(kinematic viscosity) versus temperature^{-1} for automotive diesel fuel, pure biodiesel and the analyzed vegetable oils.

the experimental data have been adjusted by means of a statistical model it is highly recommended to establish a criterion to measure the goodness of a fit [40]. For this purpose the F-test was applied. Using this approach, the regression model is statistically significant to a fixed confidence level —usually set to 95%— if the following relationship is adhered to [41],

$$F_{calc} > F_{tab} \qquad (9)$$

F_{tab} being the tabulated value of the Fisher-Snedecor distribution with ν_1 and ν_2 degrees of freedom for a fixed significance level $1-\alpha$.

Results shown in Table 4 clearly indicate that the density— temperature curves of the studied vegetable oils, diesel fuel and pure biodiesel can be adjusted by means of a straight line, resulting in significant statistics outcomes in all cases with a confidence level of 95%. Additionally, high determination coefficients were obtained for the whole set of samples analyzed.

3.2. Kinematic viscosity

The kinematic viscosity is the other key factor to take into account in order to achieve optimal fuel atomization.

The kinematic viscosity of the different vegetable oils, pure biodiesel and diesel fuel were measured from 10 °C to 140 °C according to the method explained in Section 2.1.2 and are shown in Table 5.

Table 5 shows that diesel fuel viscosity is quite inferior to the viscosity of the vegetable oils studied for the whole range of temperatures analyzed. It also indicates that for all analyzed vegetable oils, a temperature of 120 °C is enough to ensure that viscosity is below 6 mm^2 s^{-1} [18,19]. As explained in Section 3.1, this ceiling value may be lower depending on the type of engine dealt with.

In order to characterize the temperature dependence of the kinematic viscosity, a least-squares linear fit should be performed according to Equation (5). The resulting dependencies are shown in Fig. 2.

Table 6 shows a summary of the most relevant parameters related to the $\log_e$(viscosity)—temperature^{-1} fit obtained by applying Equation (5) when analyzing the whole set of samples.

Results shown in Fig. 2 and Table 6 indicate that Equation (5) is clearly fulfilled when dealing with the studied samples which in all cases obtained very high determination coefficients. Similar to other results, the outcomes were noteworthy with a confidence level of 95% for all the samples analyzed.

3.3. Relationship between the kinematic viscosity and the density

As explained in Section 2.1.3, it is valuable to have a mathematical expression linking density and viscosity of a given fuel or vegetable oil. Using this approach, by measuring the vegetable oil density, which is simple and fast, its viscosity can be estimated.

For characterizing the density-viscosity dependence, a least-squares linear fit should be carried out according to Equation (7), resulting in the dependencies shown in Fig. 3

From Fig. 3b it is deduced that there exists a linear relationship between density and the inverse of the square root of the kinematic viscosity, as stated in Equation (7). Table 7 shows a summary of the most relevant parameters related to density-viscosity$^{-1/2}$ fit obtained by means of Equation (7) for the whole set of samples analyzed.

Results shown in Fig. 3 and Table 7 indicate that Equation (7) is accomplished when dealing with the studied vegetable oils, diesel fuel and pure biodiesel obtained notably high r^2

Table 6 — Important parameters of the loge (kinematic viscosity) versus temperature-1 fit.						
Sample	A	B	C	r^2	F_{calc} ($\times 10^4$)	F_{tab}
Diesel fuel	−1.2202	−499.62	373853.59	0.999949	23.3391	4.7472
Biodiesel	−0.8412	−598.31	412410.30	0.999957	27.7126	4.7472
Rapeseed	2.5315	−2724.34	951274.72	0.999965	34.5676	4.7472
Sunflower	1.9493	−2358.16	893322.03	0.999928	16.6119	4.7472
Soybean	2.7247	−2801.29	948792.52	0.999929	16.9468	4.7472
Palm[a]	4.5613	−4444.00	1313500.49	0.998765	0.7277	5.1174
Corn	2.1769	−2469.25	902448.54	0.999838	7.3942	4.7472
Grapeseed	1.7625	−2154.47	837480.85	0.999856	8.3568	4.7472

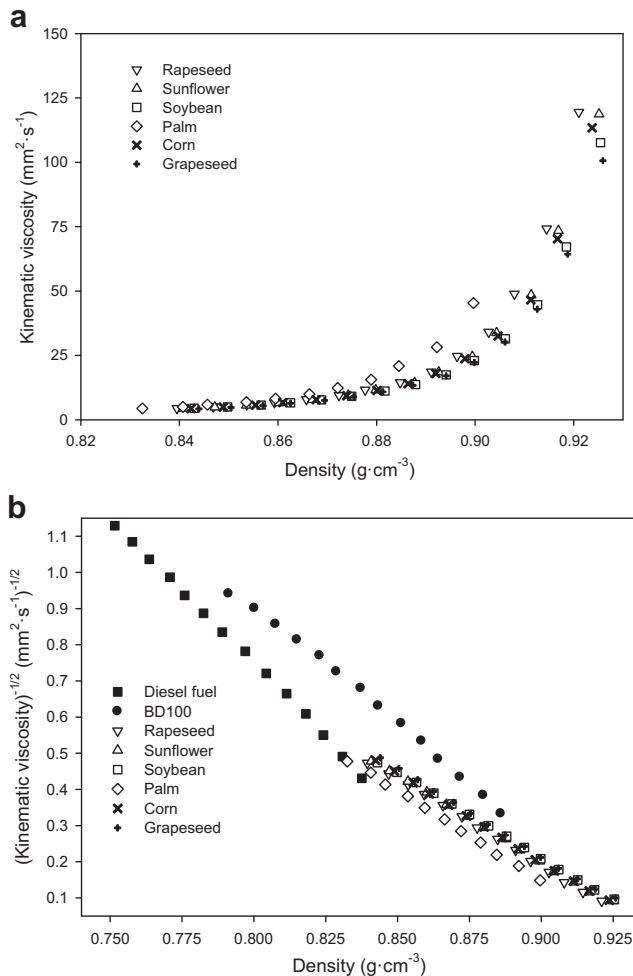a Analysis done for T ≥ 40 °C, as palm oil is solid below 40 °C.

a

b

Fig. 3 – (a) Dependence of density with kinematic viscosity for the analyzed vegetable oils. (b) Dependence of density with (kinematic viscosity)$^{-1/2}$ for automotive diesel fuel, pure biodiesel and the analyzed vegetable oils.

values in all cases. Additionally, results were quite favorable showing a confidence level of 95% for all the samples studied. Table 8 shows the prediction errors in the density-viscosity fit.

Results presented in Tables 7 and 8 indicate that for the analyzed samples a good estimation of the viscosity can be achieved from the measure of the density.

Table 7 – Important parameters of the density versus viscosity$^{-1/2}$ fit.

Sample	D	E	r^2	F_{calc} ($\times 10^4$)	F_{tab}
Diesel fuel	7.1833	−8.0456	0.9989	1.1331	4.7472
Biodiesel	6.1125	−6.5067	0.9971	0.4123	4.7472
Rapeseed	4.5331	−4.8285	0.9990	1.2986	4.7472
Sunflower	4.4707	−4.7447	0.9988	0.9804	4.7472
Soybean	4.4546	−4.7147	0.9993	1.8284	4.7472
Palm[a]	4.6144	−4.9634	0.9990	0.9283	5.1174
Corn	4.5604	−4.8440	0.9993	1.8063	4.7472
Grapeseed	4.5744	−4.8436	0.9991	1.3833	4.7472

a   Analysis done for $T \geq 40$ °C, as palm oil is solid below 40 °C.

Table 8 – Error analysis of the density-viscosity fit for the analyzed samples.

Error (%)	Max.	Min.	Average
Rapeseed	7.62	0.24	2.33
Sunflower	8.41	0.03	2.46
Soybean	4.44	0.14	1.84
Palm	4.54	0.38	1.79
Corn	4.35	0.22	1.62
Grapeseed	5.27	0.10	1.40

4. Conclusion and discussion

As mentioned, it is well known that both density and even more viscosity have a profound impact on the combustion efficiency of diesel engines, thus having a notable influence on their expected life.

In this study the temperature dependencies of density and viscosity of several commonly used vegetable oils, diesel fuel and pure biodiesel were measured and described by means of specific mathematical expressions. Furthermore, the density-viscosity dependence was analyzed, showing that a good estimation of the viscosity can be obtained from the measure of the density, which is a simple and time effective process.

Results of this research show that the analyzed vegetable oils require preheating to 120 °C minimally to match the studied physical properties of automotive diesel and biodiesel fuels. However, it is important to note that this temperature requirement depends on engine types and configurations.

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