Analysis of 22 vegetable oils’ physico-chemical properties and fatty acid composition on a statistical basis, and correlation with the degree of unsaturation

Evangelos G. Giakoumis

Internal Combustion Engines Laboratory, Thermal Engineering Department,
School of Mechanical Engineering, National Technical University of Athens, Athens, Greece

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ABSTRACT

The aim of the current work was to gather the largest possible sample of published data for vegetable oils properties, and conduct a statistical analysis in order to evaluate average values for all properties and for their fatty acid composition. A second objective was to investigate possible correlations between the properties and the degree of unsaturation. In order to achieve both tasks, the available literature on vegetable oils properties and their fatty acid composition was scanned from many well-established databases. In total, 695 papers were gathered that provided 550 different data series of oils properties and 536 of fatty acid composition, for 22 different oils. From the statistical analysis, collective results were derived for each property and quantified based on the specific oil. The effects of unsaturation were investigated too with separate best-fit linear curves provided for each interesting property with respect to the average number of double bonds. Unlike biodiesels, however, only a few (moderately) significant statistical correlations could be established between the vegetable oils properties and the degree of unsaturation, namely for cetane number, cloud and pour point and oxidation stability.

Keywords: Vegetable oil; Fatty acid composition; Degree of unsaturation; Statistical analysis; Properties

1. Introduction

An extensive research has been carried out in the last decades regarding the use of biofuels in engines, as well as the production of biofuels and alternative fuels in general. This is not surprising since fuels made from agricultural products succeed in reducing the dependence on oil imports, while at the same time supporting local agricultural industries and enhancing the local economy and energy security [1–4]. Biofuels also offer significant advantages with respect to sustainability, as well as reduced greenhouse gas, and sometimes even pollutant, emissions [5,6] when burned in internal combustion engines. The term biofuel refers to any fuel that derives from biomass, such as sugars, vegetable oils, animal fats, etc. One peculiar aspect of certain biofuels, namely vegetable oils and biodiesels, is the fact that they are produced from a variety of feedstocks. This results, inevitably, in their properties differing, sometimes considerably, affecting also their combustion characteristics and emissions from engines.

The research group involving the author has studied broadly the use of biofuels in engines, under both steady-state [7] and transient conditions [5,8]. Moreover, two extensive statistical analyses have been conducted that aimed in identifying and analyzing the effects of the biodiesel originating feedstocks on engine emissions [9], and on the properties of the fuel [10]. In the current work, the focus is now on vegetable oils.

Vegetable oils, as do animal fats, primarily consist of triglycerides; the latter are characterized by a three-carbon backbone with a long hydrocarbon chain attached to each of the carbons. The advantages of vegetable oils as diesel fuel, apart from their renewability, are the minimal sulfur and aromatic contents (particularly appealing to large engine applications), the higher flash point (hence safer storage), the higher lubricity (better operation of the fuel pump), and the higher bio-degradability and non-toxicity. However, there are certain properties of vegetable oils that render them, in general, incompatible with automotive diesel fuel, hence their use and investigation is rather limited, at least compared to biodiesels [11–21]. In particular, it is:

- their high kinematic viscosity which prohibits fast and successful fuel atomization, ultimately leading to incomplete combustion and elevated emissions;
- their relatively low cetane number, which prolongs the ignition delay and results in abrupt combustion of larger amount of fuel (with obvious effects on combustion noise radiation); as well as
- their lower calorific values (compared to conventional diesel fuel) that require larger amount of fuel to be injected for the same engine output.

Thus, the use of vegetable oils in vehicular applications is rather narrow, and only in relatively small blend ratios or for a very short time. Otherwise, serious problems may be experienced in the form of injector coking with trumpet formation, piston oil-ring sticking, carbon deposits as well as thickening and gelling of the engine lubricating oil [21–23]. To avoid these problems, micro-emulsification with methanol or ethanol, preheating (to decrease the kinematic viscosity), cracking, and, of course, conversion into biodiesels through the transesterification process are the usually applied techniques [3,24,25]. Another issue that has arisen in the recent years is that the use of vegetable oils, or vegetable oils derived biodiesels, in engines seems to influence unfavorably both the availability and prices of edible oils, particularly in the poorer regions of the world; not surprisingly, non-edible oils such as jatropha and karanja are gaining increasing interest and even more so their biodiesel derivatives [6,16–19].

Returning to the aforementioned, unfavorable for vehicular applications, values of vegetable oils' cetane number, viscosity and calorific value, these are actually quite close to the specifications of heavy fuel oil used in industrial or marine low and medium-speed diesel engines. Therefore, vegetable oils (especially palm, rapeseed and jatropha) have emerged as a viable fuel alternative for the latter category of engines/applications; hydrotreated vegetable oils is an alternative option here (to diesel or biodiesel), although, at the moment, in small quantities [26–28]. Another engine application where the use of vegetable oils is quite common is agriculture [29]. DIN 51605 regarding rapeseed oil and DIN 51623 for vegetable oil specify values for density, kinematic viscosity, oxidation stability etc for oils to be used as fuels in internal combustion engines.

In any case, use of neat oils in engines would require an additional fuel supply, since starting and shutting down of the engine should be performed on conventional diesel only. This is to ensure that deposition of neat oil on various engine parts is prohibited, a fact that would detrimentally affect cold starting. In parallel, the exhaust heat of the engine could be utilized to reduce the viscosity of the intake vegetable oil through an appropriate heat exchange device [18,21].

The target of the present work is to investigate the properties of vegetable oils from as large a sample as possible. To this aim, the physical and chemical properties and the respective oils' fatty acid compositions from hundreds of published articles were gathered for a very broad range of oils, in order to analyze them statistically and:

- Calculate the average fatty acid composition of each particular vegetable oil,
- Assess the average value and standard deviation for each physical and chemical property, and compare them to those of biodiesels and conventional (light and heavy) diesel fuel, and
- Investigate possible correlations: a) between the properties themselves, and b) between the properties and the degree of unsaturation of the corresponding oil, providing also best-fit relations that can prove useful for simulations and long-term planning by administrations and international institutions.

Similar endeavors have been undertaken in the past as regards biodiesels [10,30]. On the contrary, attempts to statistically analyze vegetable oil properties have been reported in [28,31–34], however on a much smaller sample of oils than the current one, and, particularly for the latter reference, with completely different objectives.

2. Methodology

For the statistical analysis of the various vegetable oils' physical and chemical properties from all possible origins, a detailed survey of the available data was initially conducted. This covered the following well-established databases: Elsevier Science; Springer; Taylor and Francis, Wiley; SAGE, American Chemical Society and IEEE. In total, 695 articles were collected published during the last 30 years, and the data corresponded initially to 25 different vegetable oils.

From those 25 oils, three were discarded owing to lack of adequate amount of data, namely jojoba (simmondsia chinensis), grapeseed, and polanga (calophyllum inophyllum). The remaining 22 oils, for which a satisfactory amount of data was available, and which were included in the analysis are in alphabetical order (see also Figure 1 which illustrates photos of the individual oils studied)

1. Babassu; edible oil derived from the seeds of the babassu tree in South America.
2. Canola; (*can*adian *o*il *l*ow *a*cid) variation of rapeseed oil, low in erucic acid, and popular as biodiesel feedstock.
3. Castor; non-edible oil primarily used for paints, soap and as a lubricant. Found in East Africa, India and the Mediterranean.
4. Coconut; edible oil, highly saturated, mostly found in tropical areas.
5. Corn; edible oil, mostly cultivated in the U.S. and South America, and used for the production of ethanol.
6. Cottonseed; found in many areas, derived from the cotton seeds, which are considered by-products.
7. Hazelnut; edible oil of high nutrition value.
8. Jatropha; non-edible oil, considered a major biodiesel feedstock in India (and Asia in general) but also Europe and Africa.
9. Karanja; non-edible oil found in South Asia, and often used for biodiesel production.
10. Linseed; edible oil, primarily cultivated in cool regions of the world.
11. Mahua; non-edible oil found in Central and Northern India, often used for biodiesel production.
12. Neem; non-edible oil found in India and Burma.
13. Olive; very popular edible oil of the Mediterranean countries, rarely used as biodiesel feedstock owing to it high cost.
14. Palm; edible oil, mainly produced in East Asia (e.g. Malaysia), and a major biodiesel feedstock.

15. Peanut; edible oil, produced in Central and South America, but rather rarely used for biodiesel production. It is claimed that Rudolf Diesel used (or described the use of) peanut oil in a compression ignition engine.
16. Rapeseed; derived from the seeds of rape, a cruciferous crop. It is the most popular feedstock for biodiesel production in Europe.
17. Rice bran; edible oil extracted from the germ and inner husk of rice.
18. Rubber seed; found in Asia (e.g. Cambodia), sometimes used as livestock feed.
19. Safflower; one of the oldest crops, cultivated in dry environments, mostly in the U.S., Mexico, Argentina, India and Kazakhstan.
20. Sesame; edible oil, mostly found in Asia and Mexico.
21. Soybean; edible oil, planted worldwide, particularly in North and South America, also being a major biodiesel feedstock.
22. Sunflower; edible oil, particularly popular in the Mediterranean.

These 22 oils provided 550 different data series of physico-chemical properties and 536 data series of fatty acid compositions.

Figure 2 demonstrates the number of data observations and the corresponding percentage of each oil in the database. Most observations concern sunflower (49; 8.9% of the total), soybean (58; 10.5%) and jatropha (63; 11.5%), i.e. three oils that are mostly available in the Mediterranean, America and India respectively. The non-edible jatropha, in particular, seems to gain increasing interest in the last years owing to the fact that is forms a very good biodiesel feedstock, and also due to the increased research on biodiesel production from India.

At least 4% of the total observations concern each of the following oils: canola, castor, coconut, cottonseed, karanja, palm and rapeseed. In particular canola and, the closely associated, rapeseed collectively account for 11.9% of the total observations. On the other hand, the available amount of data for hazelnut, peanut and sesame was between 1.1 and 1.6% of the total (6–9 observations for each one).

During the data collection process, care was taken to avoid on the one hand duplicate entries, and on the other include only data that was actually measured by the researchers (applying the internationally accepted experimental standards) and was not just duplicated from previous works. As was also the case with previous biodiesel surveys [10,30], some markedly ‘extreme’ data was excluded from the database unless these untypical values had been reported (i.e. measured) by at least two different researchers (see also the standard deviations in Tables 1 and 3, and Fig. 5. later in the text). Moreover, only density values measured at 15°C and kinematic viscosity ones at 40°C were included in the database.

In the end, 16 physical and chemical properties were registered in the database, namely (in parentheses the number of observations for each property): Density (341); Kinematic viscosity (308); Cetane number (93); Lower heating value (73); Higher heating value (136); Iodine number (211); Flash point (157); Pour point (103); Cloud point (64); CFP point (16); Weight percentage in carbon (30), hydrogen (27) and oxygen (30); Acid value (176); Oxidation stability (46); and Molecular weight (27). Other properties such as sulfur weight content, stoichiometric ratio, glycerol content etc. were collected too but were not included in the analysis owing to the very small number of observations (less than 15, and for one or two oils only).

3. Fatty Acid Composition

Vegetable oils, as do animal fats, primarily (90–98%) consist of triglycerides and small amounts of mono- and diglycerides; other constituents of vegetable oils are phosphatides, phospholipids, tocopherols, carotenes, and traces of water [33].

Table 1 summarizes average values and standard deviations of the fatty acids’ weight percentage for all examined vegetable oils. The last column indicates the number of observations/counts for each oil. The fatty acids for which the weight percentage is given are both saturated and unsaturated, and range from octanoic/caprylic (eight carbon atoms) to tetracosanoic/lignoceric (24 carbon atoms); the chemical formula of each fatty acid, as well as its formal and common name and molecular weight, are also indicated in Table 1. Only those fatty acids with at least 0.03% weight percentage are shown in Table 1. Fatty acids vary in terms of chain length as well as number of double bonds.

An interesting observation from Table 1 is the rather high standard deviation of sunflower. This is not totally surprising, as sunflower has been studied (and cultivated) in many areas in the world, and the high standard deviation reflects the different soils, cultivation methods and weather conditions, all of which influence the oil's composition. On the other hand, other popular oils, such as canola, coconut, soybean, palm and rapeseed present a more cohesive compositional structure. Interestingly, and despite the large number of observations in the database, jatropha presents a rather large deviation too.

A clearer picture of the data presented in Table 1 is drawn in Fig. 3 that illustrates saturated, mono-unsaturated and poly-unsaturated percentage weights for all examined vegetable oils. It is reminded here that fatty acids with two or more double bonds, Cxx:2 or Cxx3, e.g. linoleic or linolenic, are termed *poly-unsaturated* [21,33,35]. Babassu and coconut are clearly the most saturated oils, containing a percentage of saturated fatty acids of the order of 84 and 90% respectively (the average value from all oils is 'only' 26%). Palm oil (49%) and the non-edible mahua (46%) are third and fourth in this ranking. On the other hand, the highest amount of mono-unsaturated fatty acids is to be found in the castor oil (92%), and this percentage is more than double the average value from all oils. Castor is followed by hazelnut (80%), olive (76%), rapeseed (63.2%) and canola (62.8%) in mono-unsaturated acids. It should be highlighted at this point that the unique mono-unsaturated and mono-hydroxylated fatty acid found in the castor oil is $C_{18}H_{34}O_3$, commonly known as ricinoleic; the latter is responsible for the oil's high kinematic viscosity and density (Table 3). Lastly, the mostly poly-unsaturated oils are safflower (75%), linseed (71%), and sunflower (68%) (all three have a percentage of poly-unsaturated fatty acids more than double the average 34% value from all oils), followed by soybean (60%), and corn (58%); cottonseed and rubber seed are very close too.

An even more detailed picture of the vegetable oils' fatty acid composition is demonstrated in Fig. 4 that shows percentages for specific important acids such as stearic, oleic, linoleic and linolenic. Clearly

a) mahua and neem excel in stearic acid, although coconut and babassu possess higher percentages of total saturated acids comprised mostly from lauric and myristic;

b) hazelnut, olive, rapeseed/canola (peanut and karanja too) are mostly rich in oleic acid (the unique ricinoleic acid found in the castor oil is demonstrated in the same sub-diagram);
c) safflower, sunflower, corn, cottonseed and soybean present the highest amount of linoleic acid;
d) linseed, rubber seed, and, to a lesser extent, rapeseed and canola have the highest amount of linolenic acid;
e) Canola, peanut and rapeseed excel in unsaturated acids with more than 20 carbon atoms, although the relevant weight values are very small (less than 2%).

In both Figs 3 and 4 (and Table 1), as expected, canola and rapeseed demonstrate (very) close compositional features.

3.1. Degree of unsaturation

In order to study the (possible) effects of the fatty acid composition on the vegetable oils' properties, the degree of unsaturation needs first to be established; the latter is commonly associated with the iodine number (detailed in Section 3.2) [3]. For the examined oils, Table 2 provides two different versions of the degree of unsaturation together with the chain length and iodine number for each oil; average values are also provided for all 22 oils. The first column of Table 2 shows the 'unweighted' degree of unsaturation; for this metric, it is assumed that all unsaturated fatty acids have the same weight irrespective of the number of double bonds (no distinction made between mono-unsaturated and poly-unsaturated fatty acids). The second column, provides a more 'accurate' value, where each unsaturated fatty acid has a weight that corresponds to its number of double bonds (termed 'fully weighted' degree of unsaturation) [35,36].

From the values of Table 2 it can be deducted that for oils with low percentages of linoleic and linolenic acid (e.g. coconut, babassu), both degrees of unsaturation assume comparable or even the same values. This is not surprising, as these oils are highly saturated. Thus, the exact formula used to calculate the effect the double bonds have on unsaturation is only marginally relevant. Notice also in Table 2 that it is again coconut and babassu that differentiate from all other oils in terms of chain length. Whereas for all the other oils, the chain length varies from 17.09 to 18.08, for babassu it is 13.62 and for coconut even lower, 13.13.

As expected, a high correlation between the 'fully weighted' degree of unsaturation and the iodine number ($R^2=0.966$) is evident in Table 2. Thus, it will be this degree of unsaturation, i.e. the average number of double bonds that will be used in the correlation investigation in Section 4.

Lastly, and comparing the results from Table 2 with those reported in the earlier biodiesel survey [10], it is clear that the transesterification procedure does not alter the fatty acid carbon chain of the oil. As a result, the degrees of unsaturation of the examined in this work vegetable oils, and those of the corresponding biodiesels in Ref. [10], are practically the same.

3.2. Iodine value

The most typical metric used to determine the degree of unsaturation in a vegetable oil/animal fat/methyl ester is the iodine number (IN), also known as iodine value (IV). This number indicates the mass of iodine (I_2) in grams that is necessary to completely saturate, by means of a stoichiometric reaction, the molecules of 100 g of a given oil [37,38]. The (average) iodine values of the examined oils in the database, as Table 3 indicates, range from 9.4 (for coconut, which is the most saturated one) to 171.9 (for linseed, which is the most unsaturated one); the average value from all 22 oils is 97.47. In general, high iodine values indicate propensity for polymerization resulting in deposit formation [3]. In [26], a maximum IN of 125 is recommended for non-transesterified biofuels to be used in large marine four-stroke diesel engines, and in [27], another major large engines manufacturer suggests maximum IN of 120. It seems then that soybean, rubber seed, sunflower and linseed should be excluded from use in these applications.

4. Physical and chemical properties, and unsaturation effects

In this section, the most important physical and chemical properties of the vegetables oils will be discussed and the (possible) effects of unsaturation will be investigated. To this aim, Table 3 will be used, summarizing average values and standard deviations for the examined physical and chemical properties of all vegetable oils in the database. This table should be studied in conjunction with the two-page Fig. 5 that illustrates graphically its most important data. It should be pointed out that in Fig. 5 the vegetable oils are presented in order of increasing degree of unsaturation (instead of alphabetically as was the case in Figs 3 and 4). As mentioned earlier, 16 properties were registered in total, and summarized in Table 3, i.e. those for which a relatively large number of entries was available. From these, the most important 12 are illustrated in Fig. 5.

One very important feature in Fig. 5 is the standard deviation that highlights the high, in some cases, disparity in the reported results owing to differentiations in the composition of the oil as well as the measuring procedure and accuracy. This is, among others, the case for cetane number and density (among the most important attributes of a fuel). The same can be said for most of the ‘secondary’ properties such as the cold flow ones and acid value. It is rather surprising that for many oils, not even a single observation for cetane number has been reported, and the same holds true for the lower heating value.

Further, Table 4 provides the Pearson correlation coefficients between the various examined properties. Those correlations with coefficient at least 60% are highlighted (60–79% in green; higher than 80% in blue). Only seven correlations merit the distinction ‘high’ (blue colored), whereas 17 more are highlighted in green. In total, there are 24 correlations, out of 105, that present a Pearson coefficient at least 60%. Obviously, the vegetable oil properties do not seem to correlate satisfactorily with each other. On the contrary, in the earlier biodiesel survey [10], the respective numbers were much higher, indicating a superior degree of correlation between the respective biodiesel properties. A possible explanation for this is the lower reliability of the (vegetable oils) literature data.

4.1. Cetane number

The cetane number (CN) is, undoubtedly, one of the most important/critical properties a fuel intended to be used in a compression ignition engine should possess.

It describes the ignitability of the fuel, a feature particularly critical during cold starting engine conditions. As is known from the literature, low cetane numbers result in long ignition delays [39]. Conversely, the higher the cetane number, the faster the auto-ignition of the fuel.

The cetane numbers in the vegetable oil database range from 31.2 (for linseed), to 52.3 (for mahua); average value is 41.45, predictably low for a vegetable oil to be used as neat fuel in a diesel engine. It is reminded here that European specifications require CN of at least 51, and U.S. ones 47, for a fuel to be considered compatible with *vehicular* diesel engines. Hence, in Europe only mahua could be accepted in neat form. On the other hand, for *large marine* applications, a CN of at least 40 is recommended [26], hence karanja, peanut, rubber seed, sunflower and linseed should be rejected (rice bran, cottonseed, corn and soybean only marginally reach the recommended target). It should be pointed out, however, that the number of observations for CN was rather limited in the database, a fact that is also reflected into rather high standard deviation in Table 2 and Fig. 5. Since the literature on vegetable oils combustion in compression ignition engines is way smaller than that of biodiesel, it is not surprising that not many values were found.

Figure 6 illustrates the correlation between cetane number and degree of unsaturation for all oils excluding linseed (babassu, canola, coconut, hazelnut, and sesame are also not included in Fig. 6 because no measured CN values were found in the literature). The degree of correlation assumes a moderate value of 0.69 (0.79 in the biodiesel survey of 2012 [10]). Clearly, increasing the unsaturation level, i.e. as the composition becomes richer in linoleic and/or linolenic acids, reduces the CN, hence saturated oils are better suited for combustion in a diesel engine. From Table 4, no other noteworthy correlation between CN and another property was established (except unsaturation). On the contrary, noteworthy correlations between *biodiesel* CN and other FAME properties, namely density, LHV, viscosity, cloud and pour point, oxygen content, T_{90} distillation temperature and stoichiometric air–fuel ratio were established in [10]. In general, cetane number is a function of both the degree of unsaturation *and* the molecular weight (or the number of carbon atoms) [3]. To this aim, a more detailed approach than the one of Fig. 6 was undertaken for the available data sample (12 oils), relating CN with both the degree of unsaturation (DU) and the chain length (CL), and the resulting correlation is provided below

$$CN = 34.62 + 1.239 \cdot CL - 12.086 \cdot DU \qquad (1)$$

Equation (1) proves statistically strong, with coefficient of determination R^2=0.856, and standard error 2.13. From Eq. (1), two, well-known in past research (e.g. [2,3]), trends are established, namely: a) the more unsaturated the oil (higher number of double bonds), the lower the CN, and b) increasing the molecular weight or the number of carbon atoms, increases the cetane number.

4.2. Density

The density of a material or liquid is defined as its mass per unit volume. Vegetable oils (methyl esters too) possess higher density than conventional diesel fuel. This means that diesel engine fuel pumps, which operate on a volumetric basis, will inject larger mass of vegetable oil (or biodiesel) than neat diesel fuel, a fact that will influence the air–fuel ratio in the engine.

In contrast to cetane number, values for density have been reported for all vegetable oils in the database. However, here too the standard deviation is rather high. The average densities reported range from 899.5 (peanut oil) to 952.5 kg/m^3 (castor oil), with the overall average value from all 22 oils being 918.76 kg/m^3. The latter is almost 11% higher than the density of the conventional diesel fuel (830 kg/m^3), and 4.5% higher than the respective average biodiesel value (880 kg/m^3) from [10]. For large marine four-stroke engines, the recommended range of acceptable densities is 900 to 930 kg/m^3 according to MAN [26]; this means that only castor and rice bran, and (marginally) peanut are not acceptable. Even higher values, i.e., 991 kg/m^3, are considered acceptable by Wärtsila [27], meaning that even the castor oil is not out of question.

The correlation between density and unsaturation was found to be very weak, practically non-existent. In contrast, a strong correlation between density and degree of unsaturation of the corresponding methyl esters had been established in [10]

(R^2=0.86). Density was found to correlate better (R^2=0.55), but still not statistically strong, when both the degree of unsaturation and the molecular weight were taken into account (this data sample included seven oils for which molecular weight values were available). If the chain length is taken into account (together with the degree of unsaturation), the correlation was poor, perhaps due to the high disparity in the reported values.

4.3. Calorific values

The lower and the higher heating values (LHV and HHV respectively) are measures of the fuel's heat of combustion. The difference between them is the water's heat of vaporization. Vegetable oils (as well as biodiesels) contain oxygen, a fact that results in a proportionally lower energy density and heating value. Thus, more fuel needs to be injected in order to achieve the same engine power output [39].

As regards the heating values, on the one hand rather few observations were found, and not always clearly distinguishing between LHV and HHV. Hence, no correlations could be established. The average vegetable oil LHV was found in the order of 36,750 kJ/kg, and for the HHV 39,450 kJ/kg. A minimum value of 35,000 kJ/kg (typical 37,000 kJ/kg) is recommended for large four-stroke engines [26], and thus, only hazelnut seems to be out of the acceptable values.

Both heating values correlate rather well with the carbon, oxygen and hydrogen content of the oil; no correlation could be established with the degree of unsaturation. In [31], a correlation between LHV and kinematic viscosity was established for the vegetable oil sample studied; no such correlation was reached, however, in the present study.

4.4. Kinematic viscosity

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear or tensile stress. For liquid fuels, the less viscous the fluid, the greater its ease of movement. As regards diesel engines, low values of viscosity are demanded for better/faster atomization of the fuel spray and subsequent decrease in the ignition delay. On the other hand, the reduced fuel leakage losses in the (mechanical) fuel pump owing to higher kinematic viscosity lead to higher injection pressures and, hence, mass of injected fuel [39].

The vegetable oils viscosity values range from 26.2 mm^2/s (linseed) to 41.3 (rice bran), with an overall mean value of 34.16 mm^2/s. This is approximately 10 times higher than the average acceptable level the European specifications for *automotive* diesel fuel dictate. The single oil that differentiates by a lot from all the other is castor, having a kinematic viscosity of the order of 239.7 mm^2/s, and is the only one to be rejected for use in large marine engines, where a maximum viscosity of 60 mm^2/s is accepted in [26] and even 100 in [27]. The extremely high castor viscosity is attributed to its rich content in ricinoleic acid. It is the vegetable oils' high molar mass and their unsaturated fatty acids that are mostly responsible for the high kinematic viscosity values [18,21]. Notice in the last column of Table 3 that the molecular masses of vegetable oils range from 850 to 880 kg/kmol, compared to 280–290 for biodiesels [10] and 170 for conventional diesel.

As was also the case with density, no noteworthy correlation could be established between kinematic viscosity and the other properties (incl. the degree of unsaturation). The correlation between viscosity and unsaturation was not very strong in the biodiesel survey too, with an R^2 value of 0.57 [10].

Clearly, the very high viscosity of all vegetable oils (one order of magnitude higher than the acceptable diesel fuel values), renders them inappropriate for use in diesel engines except with prior heating (viscosity decreases exponentially with increasing temperature), and only for relatively small blending ratios. The transesterification process, on the other hand, reduces considerably the viscosity of the methyl ester to levels comparable to (but still higher than) that of conventional diesel fuel.

4.5. Low-temperature flow properties

Cloud (CP) and pour point (PP) are the two major low-temperature flow properties of a fuel. The cloud point, in particular, is the temperature at which wax forms a cloudy appearance. CP is designated as the temperature of first formation of wax, as the fuel is being cooled. Pour point (PP), on the other hand, is the lowest temperature at which the fuel becomes semi solid, therefore it starts losing its flow characteristics, ultimately becoming unable to be pumped; PP is always lower than CP. A third, relative, property is the CFPP, i.e. the cold filter plugging point. This is defined as the lowest temperature a fuel will have problem-free flow in a fuel system. CFPP is particularly important in cold countries, as a high cold filter plugging point will clog up vehicle engines more easily. Owing to lack of adequate amount of data for the CFPP, only the pour point and the cloud point will be analyzed.

For the CP, the values of the examined vegetable oils range from -9.7^{o}C (canola) to 23.3^{o}C (for the most saturated one, coconut); average value from all oils is 4.78^{o}C. The (average) value of CP for the castor oil was found even lower than that of canola, at -14.0^{o}C, however, as Table 3 and Fig. 5 indicate, standard deviation is quite high.

The cloud point seems to have a reasonable correlation with the degree of unsaturation, as Fig. 7 demonstrates (R^2=0.742); increasing the degree of unsaturation results in a reduction in the CP, hence unsaturated oils are more favorable for cold climates. Similar results were reached in [10] regarding the CP of biodiesels (R^2 had been found lower, however, at 0.55).

For the pour point, the values range from -22.4^{o}C (rapeseed) up to 21^{o}C (again for the most saturated one, coconut), with an overall mean value of -6.11^{o}C. As was the case with the CP, PP correlates rather well with the degree of unsaturation, as Fig. 8 illustrates (R^2=0.775).

Further, the Pearson coefficients in Table 4 suggest that the only other noteworthy correlation of either CP or PP (except with the unsaturation, hence IN) is between them, and this is demonstrated in Fig. 9. The lower sub-diagram of Fig. 9 shows the correlation between the average CP and PP values for the 16 oils for which adequate data was available. A rather strong R^2 value of 0.804 is established. The upper sub-diagram of Fig. 9, on the other hand, presents the (obviously weaker) correlation between all available (53 in total) CP-PP pairs of values in the database.

4.6. Flash point

Flash point (FP) is a measure of the temperature to which a fuel must be heated such that the mixture of vapor and air above the fuel can be ignited; FP varies inversely with the fuel's volatility. As Table 3 eloquently indicates, vegetable oils (as do biodiesels [10,30]) possess much higher flash points compared to conventional diesel. Thus, their storage can be assumed much safer.

For the examined vegetable oils, average FP values range from 216.4°C (karanja) to 285.4°C (coconut), with an overall mean value of 248.4°C; the latter is 50% higher than the respective mean value of the respective biodiesel dataset [10]. As Table 4 shows, the only noteworthy correlation of FP is with the number of carbon atoms and the oxidation stability. No correlation could be established with the degree of unsaturation, and this was also the finding reached in [10] regarding the methyl esters. Based on their flash point value, all oils are within both the automotive and (recommended) large engine specifications.

4.7. Oxidation stability

The values for the oxidation stability range from 1.2 to 91.5 h, with an overall average value of 27.23 h. It should be highlighted, however, that measurements for only 10 from the 22 oils were available, hence the sample is not adequately large and safe. In any case, a correlation with the degree of unsaturation seems to exist, as Fig. 10 illustrates. From this figure, the obvious finding is that the more saturated the oil, the higher its oxidation stability. As is well known, oxidation takes place in the double bonds, therefore unsaturated oils (or methyl esters for that matter) are more prone to oxidation [40,41].

It should be highlighted at this point that some of the above-mentioned properties, such as the calorific values and the cold flow properties, can actually be determined from their chemical composition. Further, these properties are, in general, highly affected by minor components (apart from fatty acids).

Concluding this discussion, Table 5 summarizes all vegetable oils correlations reached in the current study, in comparison to their biodiesel counterparts from Ref. [10].

5. Summary and conclusion

A large amount of data was collected from a variety of electronic databases, with respect to vegetable oils physico-chemical properties and fatty acid composition. In total, 695 papers were gathered that provided 550 different data series of oils properties and 536 of fatty acid composition, for 22 different oils (babassu, canola, castor, coconut, corn, cottonseed, hazelnut, jatropha, karanja, linseed, mahua, neem, olive, palm, peanut, rapeseed, rice bran, rubber seed, safflower, sesame, soybean and sunflower).

From the collected data, average values and standard deviations were calculated and plotted for all interesting fatty acid compositions and for the respective vegetable oils' physical and chemical properties. An investigation was conducted regarding possible correlations between the various properties, and between the properties and the degree of unsaturation.

As expected, the level of unsaturation of the oil was found to influence significantly (most of) its properties. Unlike the similar biodiesel survey of 2012 however, the correlations between the oils' properties and the unsaturation (number of double bonds) was found, in general, weaker. More specifically, for the cetane number an R^2 of 0.688 was reached, for cloud point 0.742, for pour point 0.775, and for oxidation stability 0.764. The respective linear best fits were also provided for all these correlations. On the other hand, cetane number was found to correlate quite well when using both the degree of unsaturation and the chain length in the relation (R^2=0.856). It should be pointed out that the fact that vegetable oils are not typical fuels for use (or either experimentation) in vehicular internal combustion engines resulted in the collected data not being that large and statistically safe for direct comparisons between them. One notable example here is the scarcity of CN and LHV data.

In general, it was found that saturated oils (such as those derived from coconut, palm and babassu) were better in cetane number and oxidation stability, while exhibiting poorer cold flow properties. Increasing the unsaturation decreased the kinematic viscosity, improved the cold flow properties but also lowered the cetane number and deteriorated the oxidation stability. One oil that differentiated, sometimes by a lot, from the others was castor, in particular as regards density and kinematic viscosity.

Obviously, the high kinematic viscosity of vegetable oils and their lower LHV and cetane number compared to conventional automotive diesel fuel (and biodiesel) renders them unfavorable for use in vehicular applications, at least in neat form and without preheating. In any case, these properties are quite close to those of heavy fuel oil, therefore their use is not excluded from large marine engines and diesel-engined power plants.

Acknowledgements

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Nomenclature

Abbreviations

CFPP	cold filter plugging point (^{o}C)
CP	cloud point (^{o}C)
EU	European Union
FAME	fatty acid methyl ester
FP	flash point (^{o}C)
HHV	higher heating value (kJ/kg)
IN/IV	iodine number/value
LHV	lower heating number (kJ/kg)
PP	pour point (^{o}C)
R^2	coefficient of determination
T_{90}	90% distillation temperature (^{o}C)
w/w	% mass

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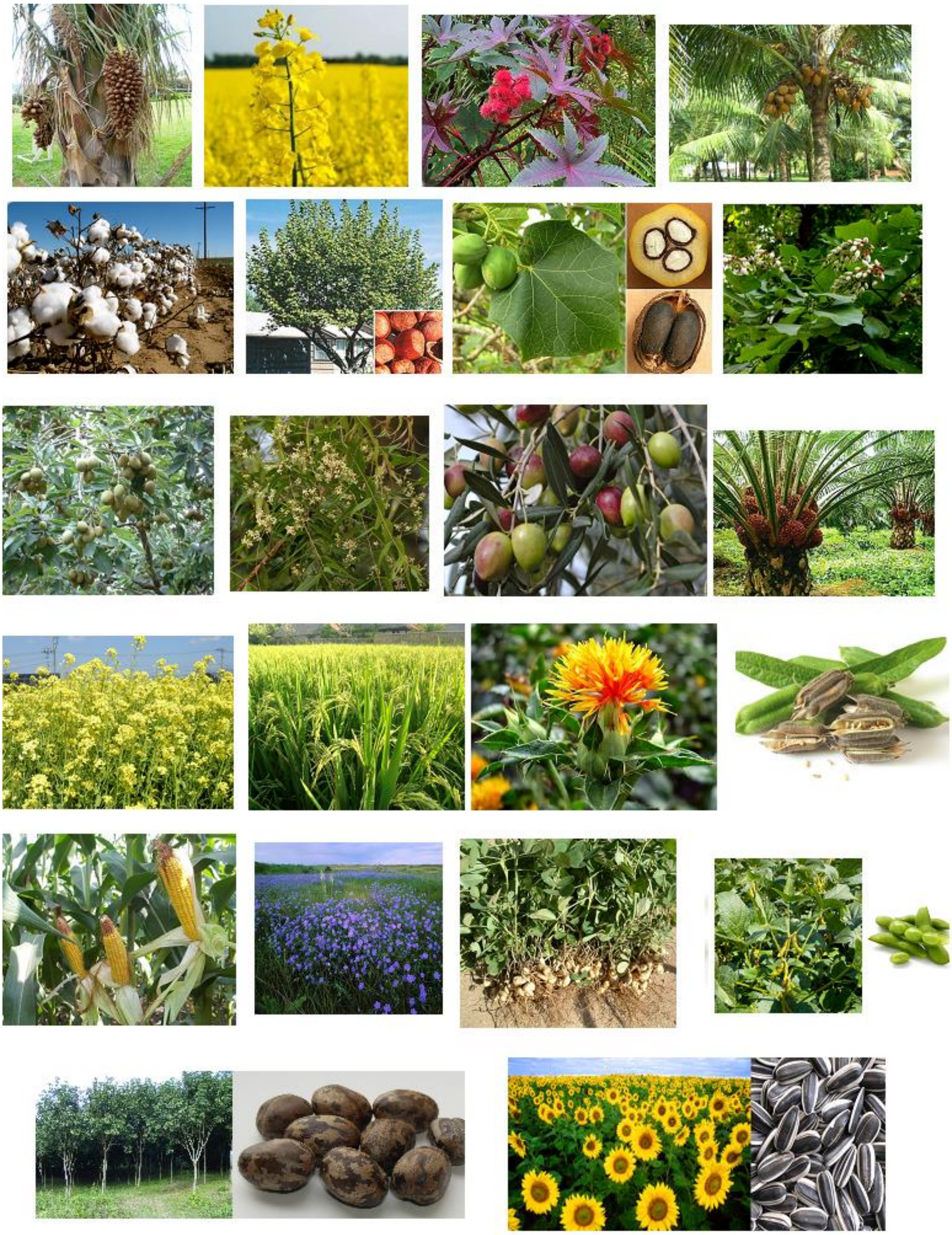

Fig. 1. Photos of the 22 studied vegetable oils (from left to right, *1st row*: babassu, canola, castor, coconut; *2nd row*: cottonseed, hazelnut, jatropha, karanja; *3rd row*: mahua, neem, olive, palm; *4th row*: rapeseed, rice bran, safflower, sesame; 5th row: corn, linseed, peanut, soybean; *6th row*: rubber seed, sunflower)

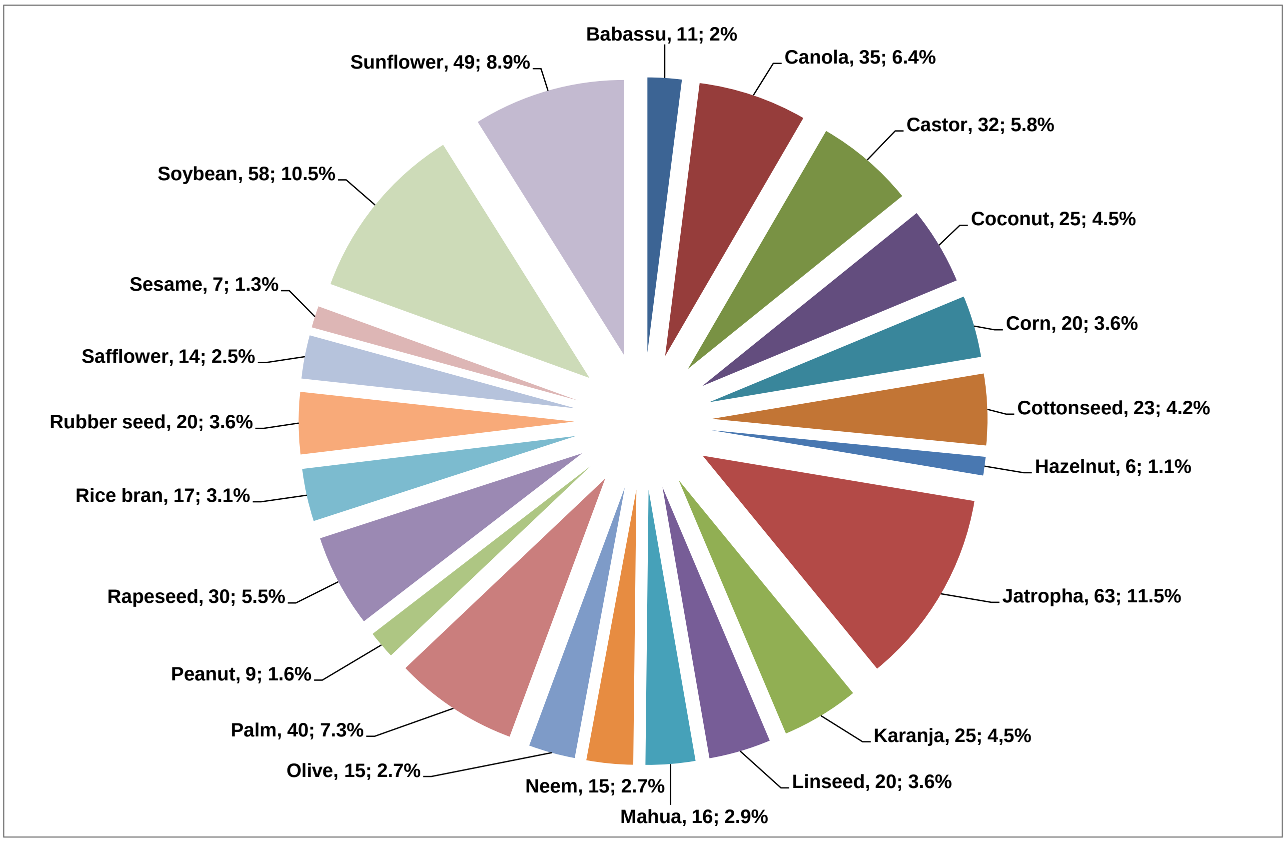

Fig. 2. Observations, and percentages with respect to the total, of the studied vegetable oils in the data set

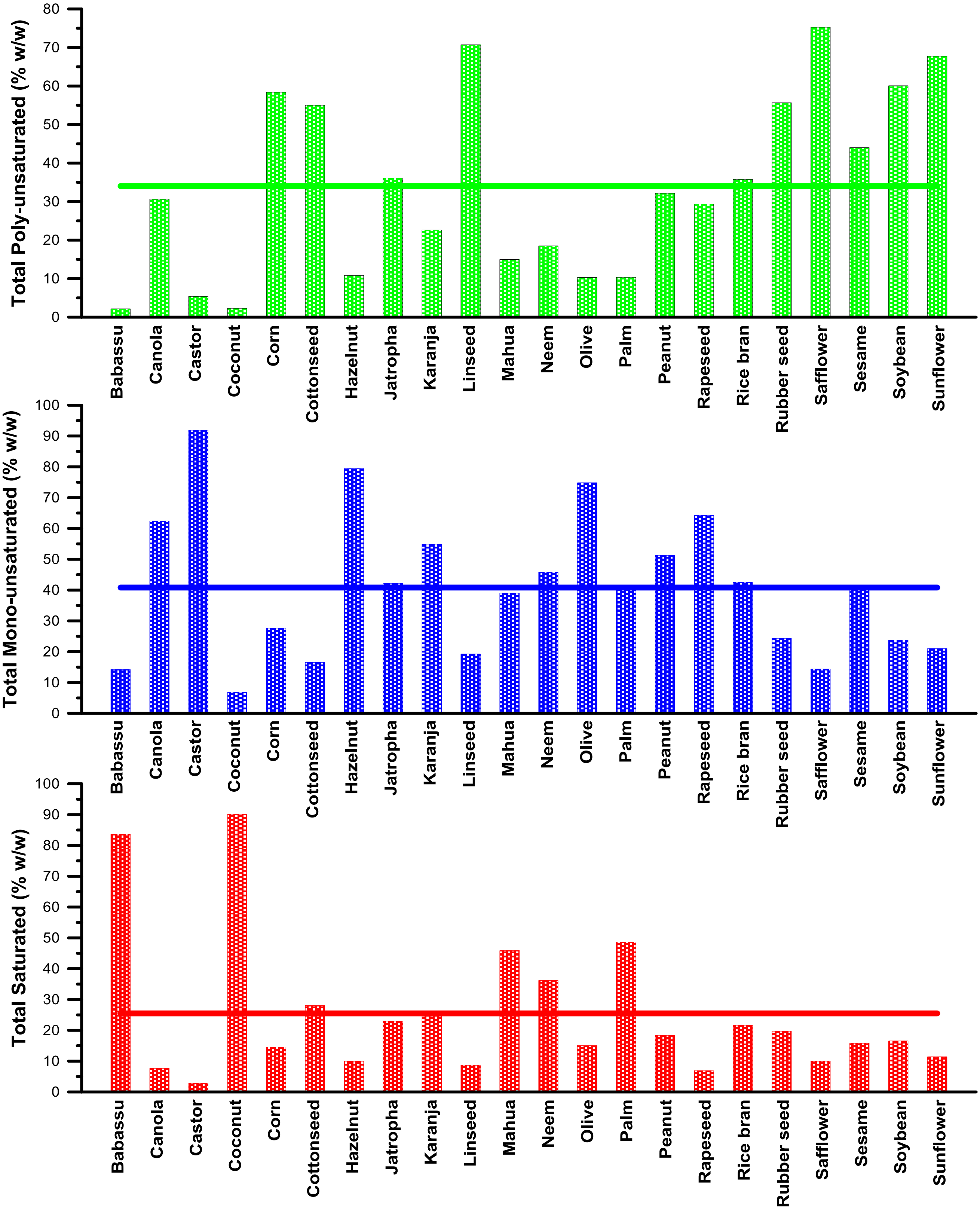

Fig. 3. Saturated, mono-unsaturated and poly-unsaturated percentage weights of all examined vegetable oils (straight lines designate average values)

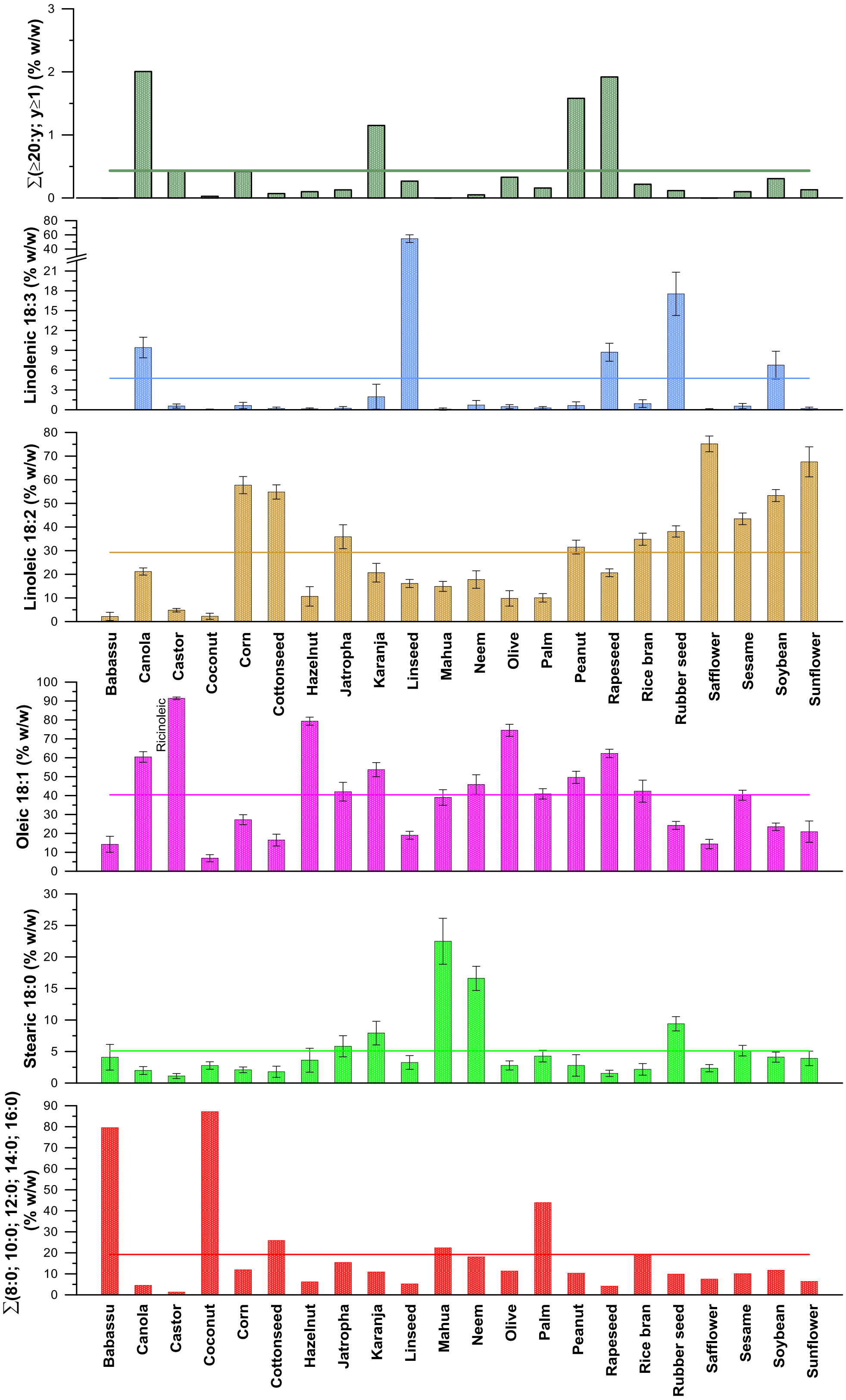

Fig. 4. Composition of each one of the vegetable oils in the data set in specific fatty acids (straight lines designate average values)

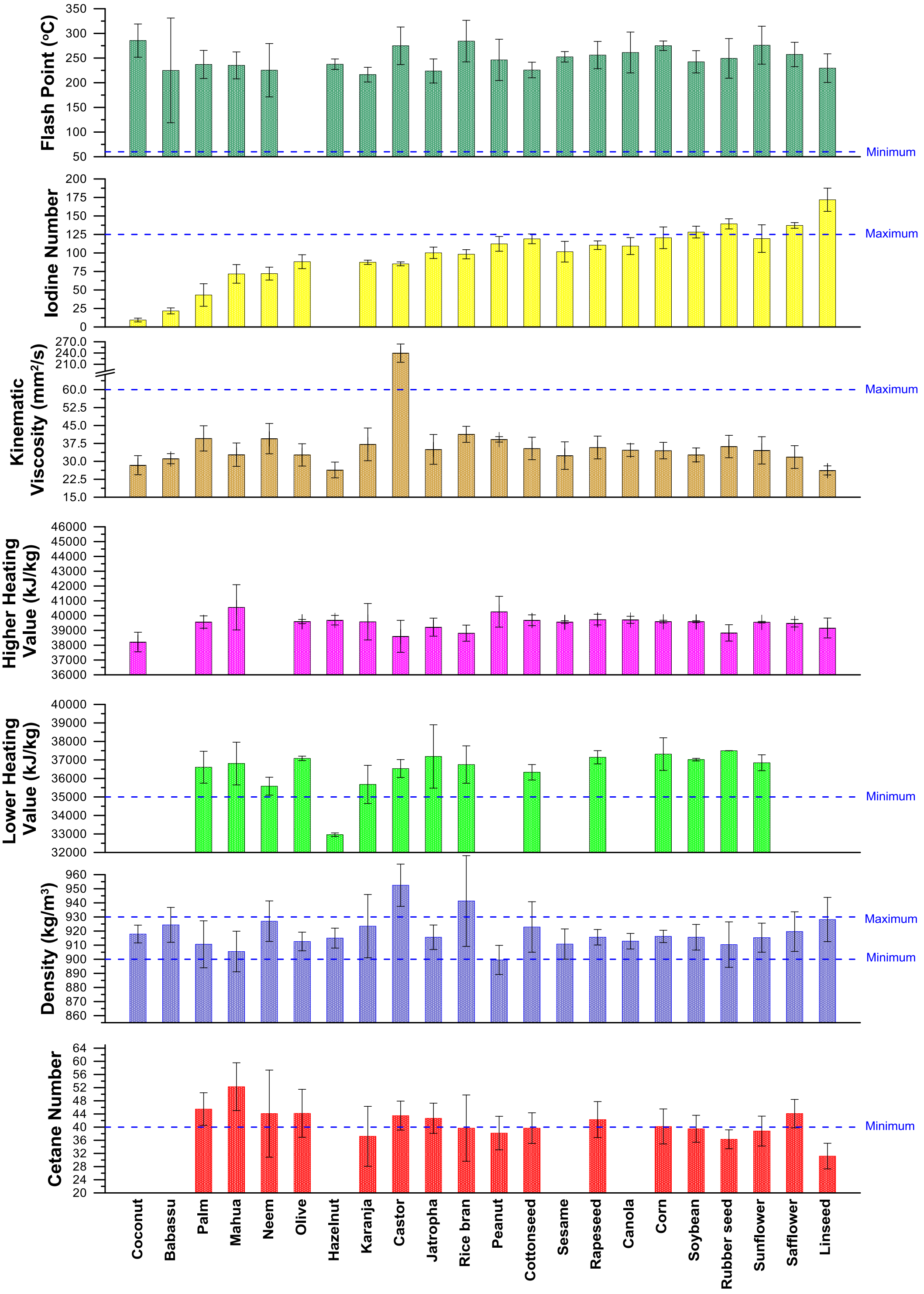

Fig. 5. Illustration of basic properties for each one of the studied vegetable oils (oils are listed in order of increasing unsaturation); horizontal dashed lines correspond to typical specifications recommended in [26] for non-transesterified biofuels to be used in large four-stroke diesel engines

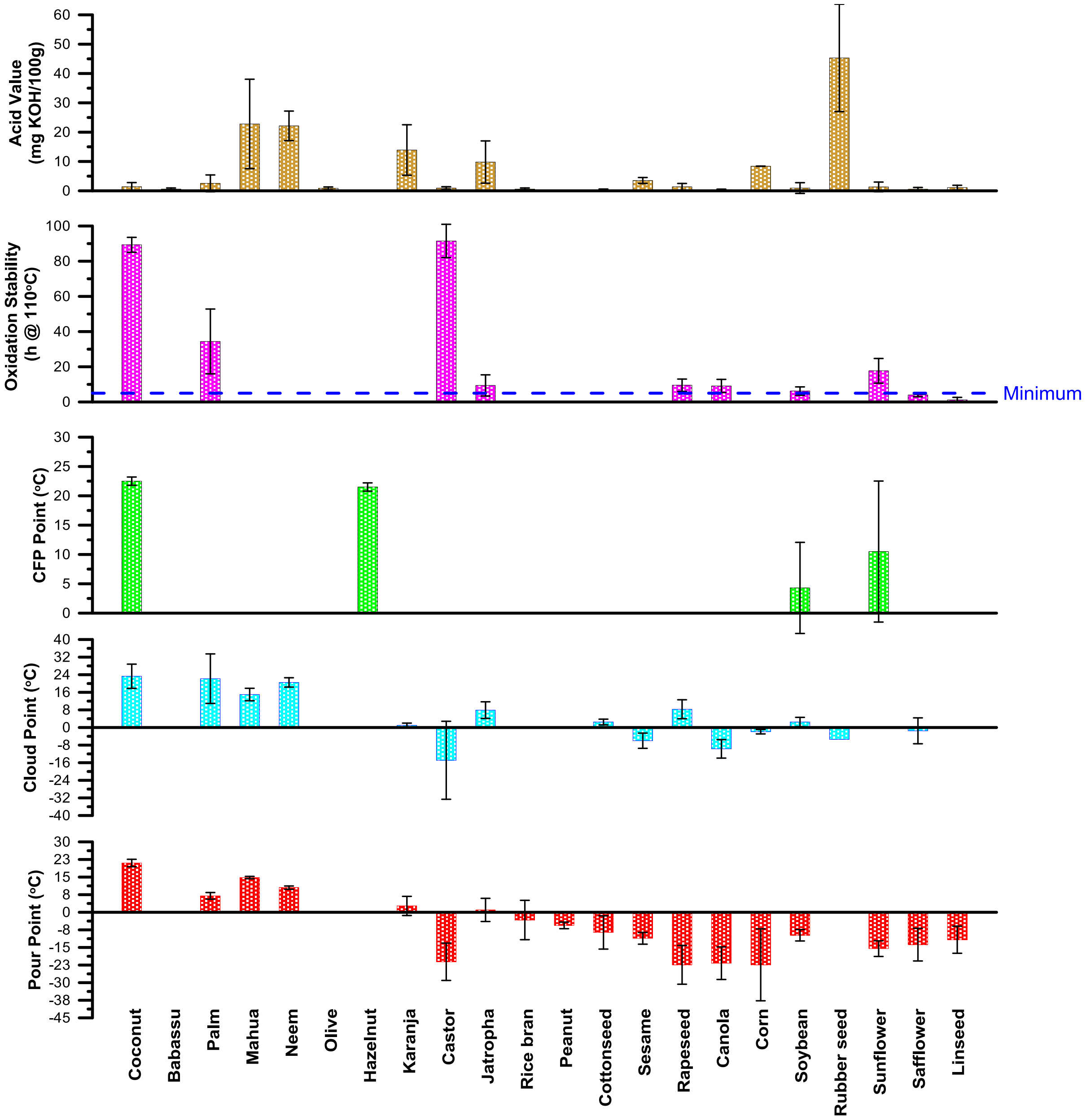

Fig. 5. *(continued)*

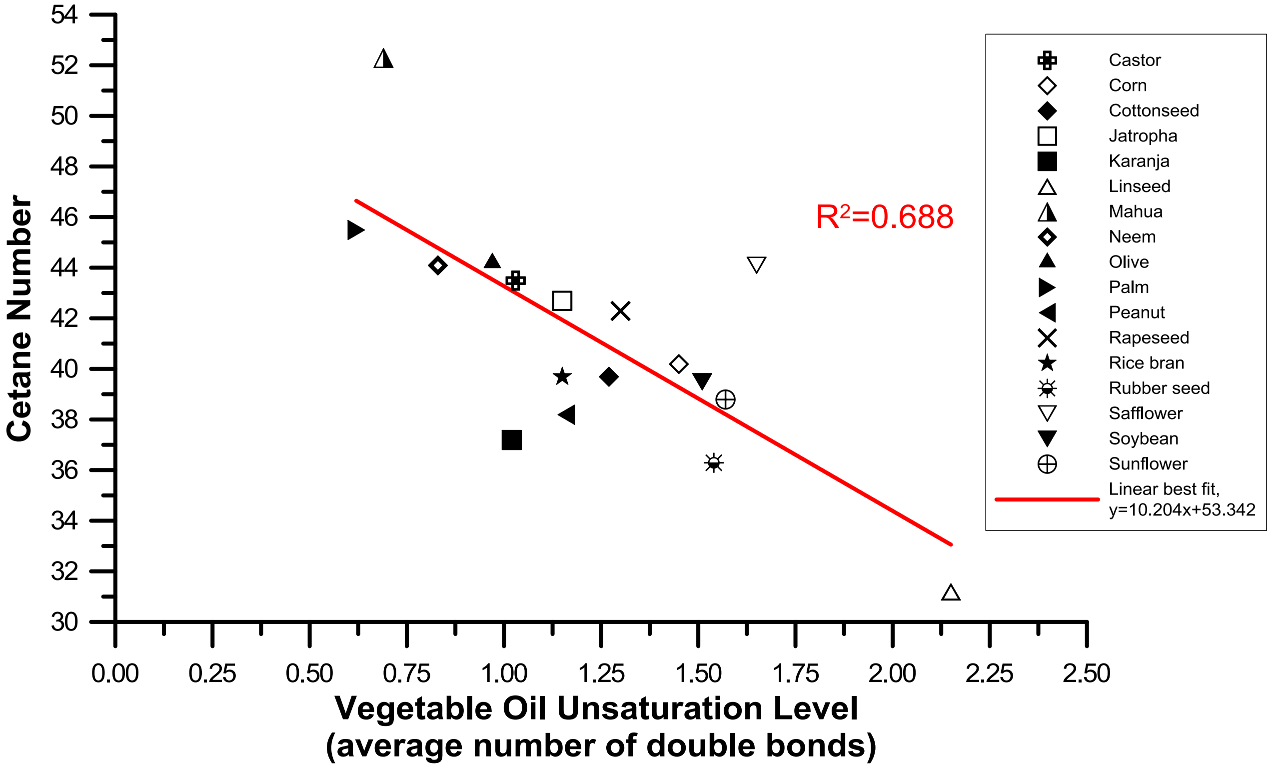

Fig. 6. Correlation between unsaturation level and cetane number for the examined vegetable oil data set (excluding babassu)

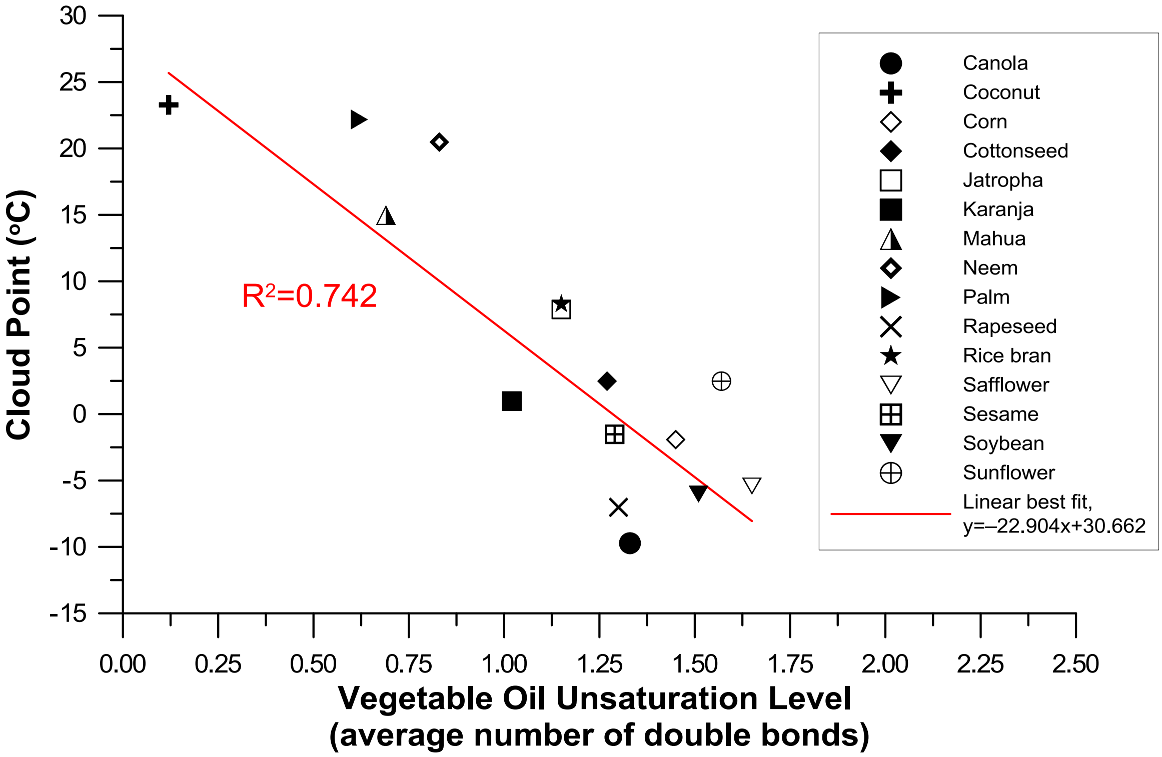

Fig. 7. Correlation between unsaturation level and cloud point for the examined vegetable oils in the data set (excluding castor)

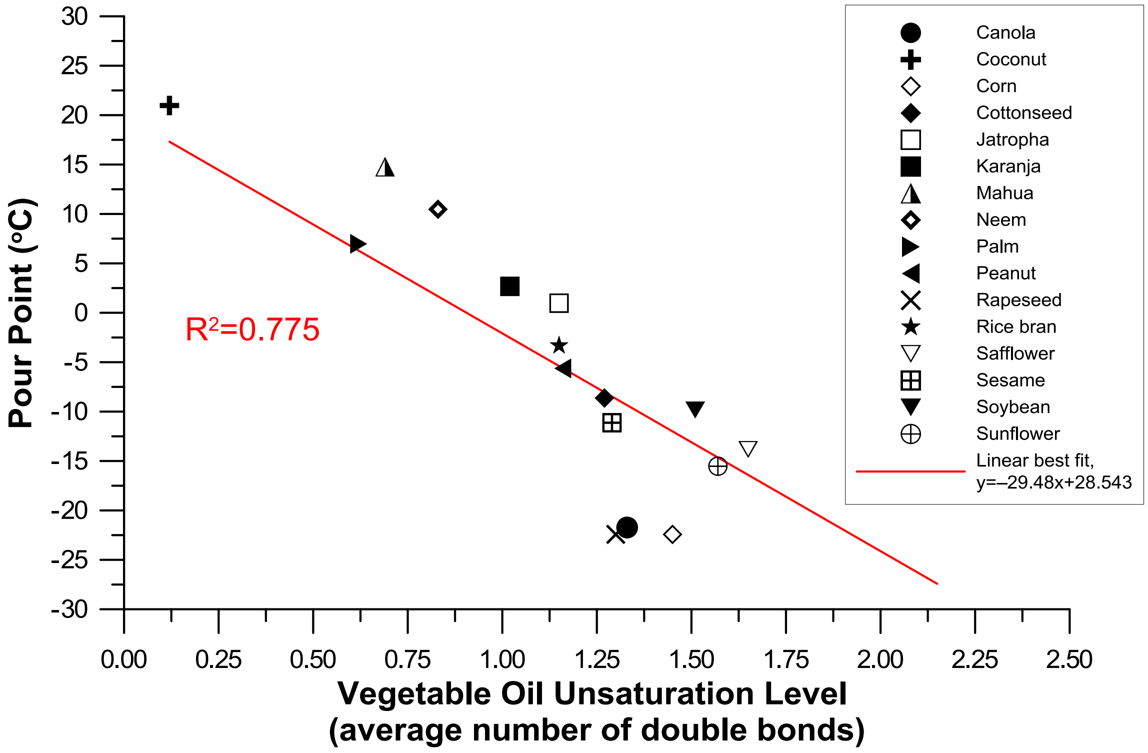

Fig. 8. Correlation between unsaturation level and pour point for the examined vegetable oils in the data set (excluding castor)

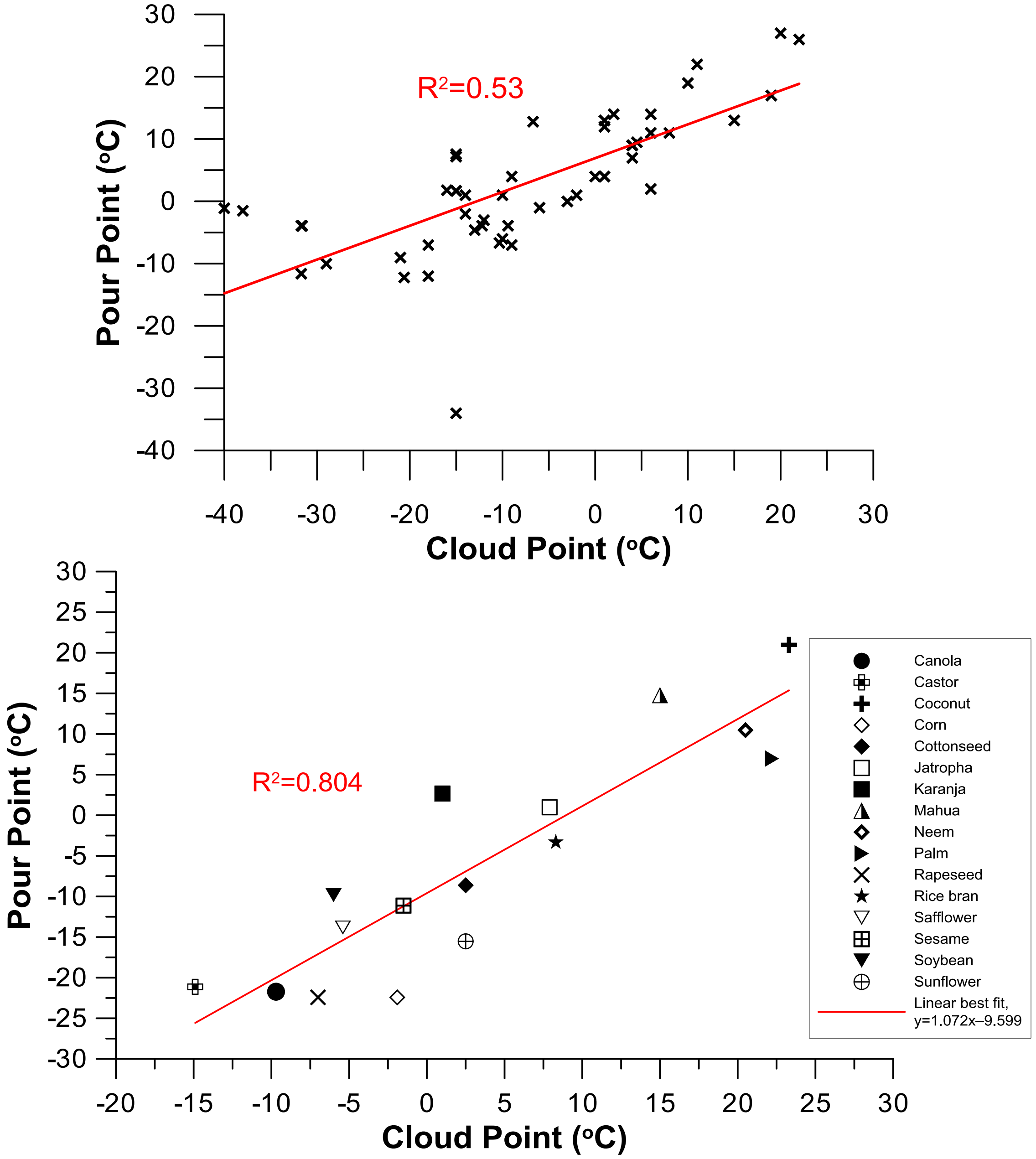

Fig. 9. Correlation between pour and cloud point for the examined vegetable oils in the data set (excluding castor); the lower diagram shows the correlation between the average values for each oil, and the upper diagram for all available pairs of values

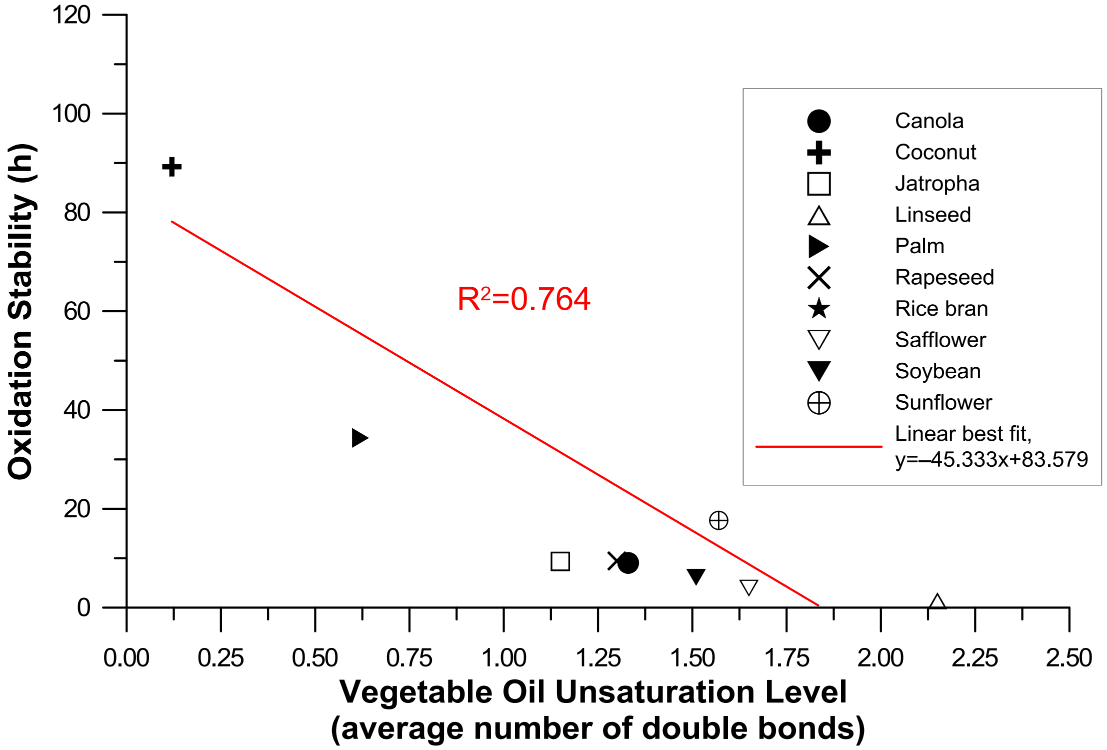

Fig. 10. Correlation between unsaturation level and oxidation for ten vegetable oils from the data set

Table 1. Fatty acid weight percentage of all vegetable oils in the data set (numbers in parentheses correspond to standard deviation; only fatty acids with at least 0.03% weight are included)

	8:0 $C_8H_{16}O_2$	10:0 $C_{10}H_{20}O_2$	12:0 $C_{12}H_{24}O_2$	14:0 $C_{14}H_{28}O_2$	16:0 $C_{16}H_{32}O_2$	16:1 $C_{16}H_{30}O_2$	17:0 $C_{17}H_{34}O_2$	18:0 $C_{18}H_{36}O_2$	18:1 $C_{18}H_{34}O_2$	18:1 OH $C_{18}H_{34}O_3$	18:2 $C_{18}H_{32}O_2$	18:3 $C_{18}H_{30}O_2$	20:0 $C_{20}H_{40}O_2$	20:1 $C_{20}H_{38}O_2$	22:0 $C_{22}H_{44}O_2$	22:1 $C_{22}H_{42}O_2$	24:0 $C_{24}H_{48}O_2$	Count
Molecular Weight (kg/kmol)	144.21	172.26	200.32	228.37	256.42	254.41	270.45	284.48	282.46	298.46	280.45	278.43	312.53	310.51	340.58	338.57	368.63	
Formal (common) name	Octanoic (Caprylic)	Decanoic (Capric)	Dodecanoic (Lauric)	Tetradecanoic (Myristic)	Hexadecanoic (Palmitic)	cis-9-Hexadecanoic (Palmitoleic)	Heptadecanoic (Margaric)	Octadecanoic (Stearic)	cis-9-Octadecanoic (Oleic)	12-Hydroxy,cis-9 Octadecanoic (Ricinoleic)	cis-9,cis-12 Octadecanoic (Linoleic)	cis-9,cis-12. cis-15-Octadecatrienoic (Linolenic)	Eicosanoic (Arachidic)	cis-11-Eicosenoic (Gondoic)	Docosanoic (Behenic)	cis-13-Docosenoic (Erucic)	Tetracosanoic (Lignoceric)	
Babassu (attalea speciose)	5.68 (1.76)	5.61 (1.72)	41.58 (8.32)	16.86 (2.51)	9.84 (2.54)	–	–	4.09 (2.03)	14.26 (4.21)	–	2.18 (1.76)	–	–	–	–	–	–	10
Canola (brassica rapa)	–	–	–	–	4.52 (1.07)	0.34 (0.32)	–	1.99 (0.62)	60.43 (2.80)	–	21.19 (1.52)	9.42 (1.55)	0.57 (0.38)	1.49 (0.79)	0.35 (0.09)	0.42 (0.26)	0.16 (0.10)	28
Castor (ricinus communis)	–	–	–	–	1.36 (0.48)	–	–	1.11 (0.40)	3.37 (0.67)	88.07 (1.91)	4.82 (0.75)	0.56 (0.31)	0.25 (0.08)	0.42 (0.14)	–	–	–	17
Coconut *(cocos nucifera)*	6.44 (2.57)	5.62 (1.45)	46.70 (5.46)	18.75 (1.69)	9.73 (1.69)	0.11 (0.10)	–	2.78 (0.59)	6.86 (1.90)	–	2.25 (1.29)	0.04 (0.07)	0.10 (0.07)	0.03 (0.02)	–	–	–	28
Corn *(zea mays)*	–	–	–	–	11.88 (1.45)	0.13 (0.17)	–	2.10 (0.45)	27.23 (2.65)	–	57.74 (3.64)	0.64 (0.48)	0.32 (0.29)	0.35 (0.47)	–	–	0.14 (0.05)	31
Cottonseed *(gossypium)*	–	–	–	0.72 (0.46)	25.19 (3.82)	0.36 (0.34)	–	1.79 (0.89)	16.47 (3.13)	–	54.83 (3.01)	0.19 (0.22)	0.22 (0.17)	0.07 (0.12)	0.11 (0.16)	–	–	26
Hazelnut *(hazel corylus)*	–	–	–	–	6.21 (1.92)	0.30 (0.09)	–	3.62 (1.89)	79.33 (2.14)	–	10.66 (4.12)	0.15 (0.13)	0.10 (0.10)	0.10 (0.17)	–	–	-	14
Jatropha *(jatropha curcas)*	–	–	0.71 (1.95)	0.27 (0.61)	14.39 (1.85)	0.69 (0.34)	0.08 (0.06)	5.83 (1.67)	42.05 (4.96)	–	35.90 (5.07)	0.23 (0.26)	0.09 (0.09)	0.10 (0.09)	0.14 (0.23)	–	1.47 (2.28)	41
Karanja *(pongamia pinnata)*	–	–	–	–	10.82 (1.54)	–	–	7.92 (1.88)	53.73 (3.74)	–	20.68 (3.94)	1.97 (1.89)	1.82 (1.22)	1.15 (0.99)	4.11 (1.56)	–	1.33 (1.23)	12
Linseed *(linum usitatissimum)*	–	–	0.03 (0.05)	0.04 (0.05)	5.18 (0.85)	0.10 (0.11)	–	3.26 (1.09)	19.04 (2.08)	–	16.12 (1.72)	54.59 (5.41)	0.09 (0.10)	0.07 (0.10)	0.10 (0.12)	0.20 (0.40)	0.03 (0.05)	19
Mahua *(madhuca indica)*	–	–	–	0.15 (0.10)	22.23 (2.40)	–	–	22.49 (3.65)	39.01 (4.11)	–	14.87 (2.11)	0.10 (0.17)	1.01 (0.55)	–	–	–	–	10
Neem *(azadirachta indica)*	–	–	0.40 (0.57)	0.18 (0.28)	17.57 (1.14)	0.05 (0.07)	–	16.60 (1.92)	45.83 (5.16)	–	17.79 (3.70)	0.72 (0.69)	1.18 (0.32)	0.05 (0.07)	0.15 (0.21)	–	0.10 (0.14)	10
Olive *(olea europaea)*	–	–	–	0.08 (0.13)	11.26 (2.57)	0.88 (0.53)	0.07 (0.04)	2.79 (0.72)	74.52 (3.17)	–	9.82 (3.27)	0.51 (0.17)	0.49 (0.29)	0.29 (0.25)	0.16 (0.07)	0.04 (0.06)	0.17 (0.19)	31
Palm (arecaceae)	0.08 (0.04)	0.06 (0.05)	0.36 (0.29)	1.13 (0.66)	42.31 (3.18)	0.17 (0.12)	0.06 (0.06)	4.27 (0.93)	40.90 (2.74)	–	10.07 (1.79)	0.28 (0.20)	0.31 (0.16)	0.16 (0.06)	0.04 (0.05)	–	0.05 (0.05)	54
Peanut *(arachis hypogaea)*	–	–	–	–	10.33 (2.22)	–	–	2.79 (1.70)	49.63 (3.21)	–	31.52 (2.92)	0.64 (0.56)	1.07 (0.40)	1.48 (1.05)	2.86 (0.77)	0.10 (0.11)	1.30 (0.73)	16
Rapeseed *(brassica napus)*	–	–	–	0.04 (0.04)	4.06 (0.81)	0.23 (0.11)	0.07 (0.12)	1.54 (0.49)	62.29 (2.23)	–	20.65 (1.65)	8.71 (1.36)	0.87 (0.78)	1.09 (0.72)	0.27 (0.25)	0.77 (0.90)	0.04 (0.07)	46
Rice bran *(oryza sativa)*	–	–	0.08 (0.09)	0.45 (0.38)	18.12 (3.42)	0.20 (0.09)	–	2.17 (0.92)	42.35 (5.81)	–	34.84 (2.56)	0.93 (0.58)	0.45 (0.25)	0.22 (0.16)	0.21 (0.09)	–	0.16 (0.26)	19
Rubber seed *(hevea brasiliensis)*	–	–	–	0.51 (0.95)	9.39 (1.13)	0.13 (0.12)	0.04 (0.05)	9.41 (1.13)	24.22 (2.12)	–	38.12 (2.38)	17.54 (3.27)	0.28 (0.29)	0.12 (0.10)	0.08 (0.08)	–	–	7
Safflower *(carthamus tinctorius)*	–	–	–	0.12 (0.12)	7.41 (1.29)	0.04 (0.05)	–	2.36 (0.57)	14.37 (2.46)	–	75.17 (3.33)	0.08 (0.09)	0.08 (0.15)	–	0.10 (0.17)	–	–	22
Sesame (sesamum indicum)	–	–	–	–	10.06 (0.67)	0.10 (0.08)	–	5.14 (0.84)	40.18 (2.65)	–	43.46 (2.46)	0.56 (0.41)	0.57 (0.06)	0.10 (0.14)	0.08 (0.05)	–	–	12
Soybean *(glycine max)*	–	–	0.08 (0.14)	0.12 (0.24)	11.50 (1.76)	0.16 (0.22)	0.04 (0.05)	4.11 (0.80)	23.50 (1.96)	–	53.33 (2.54)	6.76 (2.10)	0.32 (0.23)	0.22 (0.22)	0.27 (0.22)	0.07 (0.13)	0.13 (0.12)	91
Sunflower *(helianthus annuus)*	–	–	–	0.04 (0.05)	6.35 (1.62)	0.07 (0.07)	–	3.92 (1.15)	20.91 (5.65)	–	67.58 (6.35)	0.17 (0.23)	0.22 (0.17)	0.11 (0.11)	0.66 (0.28)	–	0.26 (0.09)	43

Table 2. Degrees of unsaturation, chain length and iodine number for all vegetable oils in the data set

Vegetable Oil	**'Unweighted' degree of unsaturation (%) ***	**'Fully weighted' degree of unsaturation (average number of double bonds) ****	**Chain length**	**Oil iodine number**
Babassu	0.16	0.18	13.62	21.7
Canola	0.92	1.33	17.99	109.3
Castor	0.97	1.03	17.99	85.3
Coconut	0.09	0.12	13.13	9.4
Corn	0.86	1.45	17.79	120.5
Cottonseed	0.72	1.27	17.47	119.1
Hazelnut	0.90	1.02	17.87	-
Jatropha	0.77	1.15	17.75	100.2
Karanja	0.75	1.02	18.08	87.4
Linseed	0.91	2.15	17.91	171.9
Mahua	0.54	0.69	17.57	71.7
Neem	0.64	0.83	17.66	72.1
Olive	0.85	0.97	17.79	88.2
Palm	0.51	0.62	17.09	43.2
Peanut	0.82	1.16	18.04	112.3
Rapeseed	0.93	1.30	18.01	110.5
Rice bran	0.78	1.15	17.64	98.3
Rubber seed	0.80	1.54	17.80	139.3
Safflower	0.90	1.65	17.85	137.2
Sesame	0.84	1.29	17.85	101.7
Soybean	0.84	1.51	17.79	128.2
Sunflower	0.89	1.57	17.92	119.4
Average values for all oils	0.75	1.14	17.39	97.5
Correlation with iodine number	R^2=0.708	R^2=0.966	R^2=0.565	–

* All unsaturated fatty acids have the same percentage weight

** Each fatty acid of the type XX:y (y≥2) has y percentage weight

Table 3. Properties of all vegetable oils in the data set (numbers in parentheses correspond to standard deviation)

	Cetane Number	**Density (kg/m³)**	**Lower Heating Value (kJ/kg)**	**Higher Heating Value (kJ/kg)**	**Kinematic Viscosity (mm²/s)**	**Flash Point (ºC)**	**Pour Point (ºC)**	**Cloud Point (ºC)**	**CFPP (ºC)**	**Iodine Number**	**Oxidation Stability (h)**	**Acidity (mg KOH/g)**	**C (% w/w)**	**H (% w/w)**	**O (% w/w)**	**Molecul. Weight (kg/kmol)**
Babassu	–	924.4 (12.38)	–	–	31.1 (2.11)	225.0 (106.1)	–	–	–	21.7 (4.03)	–	0.61 (0.37)	–	–	–	–
Canola	–	912.8 (5.50)	–	39,719 (238)	34.7 (2.64)	261.3 (41.4)	-21.7 (6.9)	-9.7 (4.2)	–	109.3 (11.41)	9.1 (3.75)	0.31 (0.26)	78.9 (1.83)	11.4 (0.72)	10.1 (2.09)	880.95 (1.48)
Castor	43.5 (4.40)	952.5 (14.97)	36,535 (485)	38,600 (1082)	239.7 (24.36)	274.9 (38.1)	-21.1 (8.0)	-14.9 (17.7)	–	85.3 (2.61)	81.5 (9.48)	0.94 (0.46)	–	–	–	887.56 (43.22)
Coconut	–	917.9 (6.28)	–	38,215 (661)	28.4 (4.00)	285.4 (33.6)	21.0 (1.6)	23.3 (5.5)	22.5 (0.7)	9.4 (2.57)	89.3 (4.25)	1.42 (1.39)	–	–	–	–
Corn	40.2 (5.32)	916.2 (4.37)	37,317 (881)	39,598 (90)	34.5 (3.45)	275.0 (9.6)	-22.4 (15.3)	-1.9 (1.0)	–	120.5 (14.64)	–	8.40 (2.97)	–	–	–	–
Cottonseed	39.7 (4.66)	922.9 (17.91)	36,333 (416)	39,687 (364)	35.4 (4.70)	225.8 (15.8)	-8.6 (7.1)	2.5 (1.3)	–	119.1 (6.63)	–	0.30 (0.31)	77.2 (0.33)	11.9 (0.01)	10.6 (0.77)	859.60 (10.75)
Hazelnut	–	915.0 (7.07)	32,959 (98)	39,693 (323)	26.4 (3.29)	237.5 (10.6)	–	–	–	–	–	–	–	–	–	–
Jatropha	42.7 (4.59)	915.6 (8.71)	37,187 (1712)	39,221 (610)	35.0 (6.23)	223.8 (24.4)	1.0 (4.9)	7.9 (3.8)	21.5 (0.7)	100.2 (7.73)	9.4 (6.03)	9.81 (7.20)	76.6 (0.56)	10.4 (0.14)	11.7 (1.41)	853.17 (65.25)
Karanja	37.2 (9.11)	923.5 (22.44)	35,676 (1032)	39,588 (1228)	37.1 (6.85)	216.4 (14.8)	2.7 (4.1)	1.0 (1.0)	–	87.4 (2.89)	–	13.92 (8.60)	–	–	–	–
Linseed	31.2 (3.90)	928.2 (15.68)	–	39,164 (674)	26.2 (1.90)	229.6 (29.0)	-11.7 (5.8)	–	–	171.9 (15.71)	1.2 (1.41)	1.09 (0.79)	–	–	–	–
Mahua	52.3 (7.26)	905.5 (14.40)	36,805 (1153)	40,561 (1527)	32.8 (4.90)	235.2 (27.3)	14.8 (0.5)	15.0 (2.8)	–	71.7 (12.54)	–	22.80 (15.25)	–	–	–	845.00 (49.50)
Neem	44.1 (13.24)	927.0 (14.38)	35,581 (484)		39.5 (6.34)	225.4 (54.0)	10.5 (0.7)	20.5 (2.1)	–	72.1 (8.73)	–	22.15 (5.04)	–	–	–	–
Olive	44.2 (7.28)	912.6 (6.59)	37,085 (121)	39,600 (141)	32.7 (4.66)	–	–	–	–	88.2 (9.39)	–	0.84 (0.47)	–	–	–	–
Palm	45.5 (4.95)	910.6 (16.64)	36,608 (862)	39,568 (418)	39.6 (5.28)	237.1 (28.4)	7.0 (1.4)	22.2 (11.3)	–	43.2 (15.22)	34.4 (18.42)	2.54 (2.87)	78.2 (2.05)	12.2 (0.92)	9.7 (2.98)	–
Peanut	38.2 (5.09)	899.5 (10.35)	–	40,263 (1040)	39.2 (1.13)	246.3 (41.9)	-5.6 (1.4)	–	–	112.3 (9.99)	–	–	–	–	–	–
Rapeseed	42.3 (5.46)	915.6 (5.48)	37,145 (357)	39,732 (361)	35.8 (4.78)	256.1 (27.7)	-22.4 (8.3)	-7.0 (4.3)	–	110.5 (5.81)	9.5 (3.51)	1.39 (1.12)	78.8 (1.39)	11.5 (0.22)	9.9 (1.12)	–
Rice bran	39.7 (10.07)	941.3 (32.17)	36,751 (1010)	38,816 (545)	41.3 (3.36)	284.4 (42.1)	-3.3 (8.4)	8.3 (9.0)	–	98.3 (6.21)	–	0.59 (0.39)	–	–	–	–
Rubber seed	36.3 (2.87)	910.4 (16.12)	37,500 (0)	38,832 (554)	36.2 (4.68)	249.3 (40.2)	–	–	–	139.3 (6.86)	–	45.32 (18.31)	–	–	–	–
Safflower	44.1 (4.32)	919.6 (14.06)	–	39,485 (254)	31.8 (4.76)	257.3 (24.7)	-13.8 (7.0)	-5.4 (5.9)	–	137.2 (3.82)	4.0 (1.04)	0.54 (0.61)	–	–	–	–
Sesame	–	910.8 (10.73)	–	39,565 (92)	32.4 (5.76)	252.5 (10.6)	-11.1 (2.5)	-1.5 (3.5)	–	101.7 (14.02)	–	3.52 (1.02)	–	–	–	–
Soybean	39.5 (4.10)	915.6 (9.10)	37,017 (69)	39,594 (65)	32.7 (2.90)	242.4 (22.5)	-9.8 (2.4)	-6.0 (2.1)	4.3 (7.8)	128.2 (7.92)	6.2 (2.37)	0.94 (1.83)	77.6 (1.21)	11.2 (0.43)	10.7 (1.39)	876.12 (31.29)
Sunflower	38.8 (4.54)	915.3 (10.30)	36,848 (429)	39,559 (51)	34.6 (5.70)	276.1 (38.4)	-15.5 (3.3)	2.5 (9.7)	10.5 (12.0)	119.4 (18.64)	17.7 (7.02)	1.33 (1.65)	77.8 (0.88)	11.6 (0.33)	10.7 (0.61)	875.51 (7.93)

Table 4. Pearson coefficients for the correlations between the various vegetable oils properties (coefficients between 0.60 and 0.79 are highlighted in green, and above 0.80 in blue

	Unsaturation	Cetane Number	Density	LHV	HHV	Kinem. Viscosity	Flash Point	Iodine Number	Pour Point	Cloud Point	Carbon	Hydr.	Oxygen	Oxidation Stability	Acidity
Unsaturation	1														
Cetane Number	-0.74	1													
Density	0.01	-0.15	1												
LHV	0.34	-0.06	-0.09	1											
HHV	-0.07	0.37	-0.26	-0.27	1										
Viscosity	-0.06	0.15	0.45	0.04	-0.25	1									
Flash Point	0.05	0.00	0.22	0.33	-0.49	0.28	1								
Iodine Number	0.98	-0.72	-0.04	0.51	-0.02	-0.08	-0.01	1							
Pour Point	-0.74	0.43	-0.18	-0.49	0.19	-0.28	-0.30	-0.72	1						
Cloud Point	-0.71	0.55	-0.20	-0.28	0.29	-0.42	-0.24	-0.70	0.80	1					
Carbon	-0.04	0.24	-0.50	0.06	0.76	0.22	0.65	-0.15	-0.59	-0.16	1				
Hydrogen	-0.35	0.13	-0.03	-0.77	0.68	0.58	0.19	-0.40	0.02	0.32	0.47	1			
Oxygen	0.35	-0.37	0.38	0.34	-0.80	-0.53	-0.37	0.42	0.24	-0.18	-0.86	-0.80	1		
Oxidation Stability	-0.74	0.39	0.55	-0.82	-0.85	0.65	0.64	-0.75	0.40	0.10	0.11	0.74	-0.47	1	
Acidity	0.01	0.03	-0.27	0.05	0.26	-0.10	-0.26	0.09	0.54	0.06	-0.63	-0.72	0.70	-0.13	1

Table 5. Comparison in the obtained unsaturation effects between the current vegetable oils analysis and the methyl esters' one from 2012 [10]

Property	**Correlation (R^2) with the degree of unsaturation for *vegetable oils***	**Correlation (R^2) with the degree of unsaturation for *biodiesels* [10]**
Cetane number	0.69	0.79
Density	—	0.87
LHV/HHV	—	0.59 / 0.42
Kinematic viscosity	—	0.57
Cloud point	0.74	0.55
Pour point	0.78	0.63
Oxidation stability	0.76	—
Carbon atoms	—	0.70
Stoichiometric ratio	—	0.69
Distillation temperature	—	0.72