Study of the flammability of vegetable oils in the combustion chamber of diesel engines

V A Markov¹, S N Devyanin², V G Kamaltdinov³ and B Sa¹

¹ Power Engineering Faculty, Bauman Moscow State Technical University, 5, 2-ya Baumanskaya Str., Moscow, 105005, Russia
² Tractors and Cars Department, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, Moscow, 127550, Russia
³ Motor Transport Faculty, South Ural State University, 76, Lenina Ave., Chelyabinsk, 454080, Russia

Email: sabovnen@bmstu.ru

Abstract. Promising biofuels for diesel engines are vegetable oils and fuels derived from them. The advantages of using biofuels in internal combustion engines were considered. The problems of using vegetable oils in diesel engines have been analyzed. It is noted that the main issues of using vegetable oils are their high viscosity and their worst flammability in the combustion chamber of diesel engines. The flammability indicators of vehicle fuels in the combustion chamber of diesel engines were considered. The most important among them is the cetane number of the fuel. The factors influencing the cetane number of vegetable oils have been determined. The dependences of the cetane number of vegetable oils on the flash point in a closed-cup, the content of oleic acid, and the content of saturated fatty acids have been obtained and analyzed. These dependences have been compared with a multi-factorial dependence of the cetane number on the basic triglyceride contents.

1. Introduction

One of the urgent problems in modern engine manufacturing is the need to find alternatives to petroleum diesel fuel (DF) and replace it with vehicle fuels produced from renewable raw materials. Recently, more and more fuels derived from vegetable oils (VOs) have been used as fuels for diesel engines [1, 2]. In different parts of the world, such as Europe, the United States, the countries of Central and Latin America, and Southeast Asia, these fuels are considered to be real alternatives to petroleum fuels. Moreover, these biofuels are used in various industries - road transport, agriculture, railway transport, and energy [3, 4]. This is due to the simplicity and environmental friendliness of obtaining VOs, the potential to improve emission performances of diesel engines fueled with these fuels, the relatively low cost of VOs, and their acceptable flammability in the combustion chamber of diesel engines.

Although there have been some problems in the operation of diesel engines using VOs and their derivatives (high viscosity, low cetane number, high freezing point, and high coking property), studies on the performance of diesel engines using these biofuels and their mixtures with other fuels, in particular, with petroleum DF, have continued [5-13]. Biofuels are expected to account for 4-6% of total vehicle fuel consumption by 2030 [3].

There are two possible ways to use VOs and their derivatives as vehicle fuels - centralized and decentralized production of biofuels [3]. The centralized production of vehicle fuels from VOs is to
process VO
nities into esters (methyl, ethyl, butyl), which are then used as diesel engine fuels. The
decentralized production is to use “pure” VO or their mixtures with petroleum DF as vehicle fuel.

In the analysis of the possibilities of using various VO to produce biofuels, rapeseed oil (RO) is
usually considered [1-3]. At the same time, other kinds of VO are grown in Russia. The structure of VO
production in Russia is as follows: sunflower oil (SuO) accounts for 86.84%, soybean oil (SO) accounts
for 7.96%, RO accounts for 4.84%, mustard oil (MuO) accounts for 0.11%, and other oils, such as corn
oil (CO), linseed oil (LO), account for 0.25% [2].

One of the problems arising in adapting diesel engines to run on VO and their derivatives is the
difference in physicochemical properties between VO and petroleum DF. Some physicochemical
properties of the most significant VO for Russia are given in Table 1. It should be noted the high
viscosity of VO and their worst flammability in the combustion chamber (CC) of diesel engines.
Therefore, if the cetane number (CN) of petroleum DF is 45 or more according to GOST 305-2013
(Diesel fuel. Technical condition), the CN of VO usually ranges from 33 to 36 (see Table 1) [3]. This
leads to a longer ignition delay, a higher rate of pressure rise in the CC, and more nitrogen oxide
emissions from the exhaust gas.

### Table 1. Physicochemical properties of petroleum DF and VO

| Physicochemical properties | DF | RO | SuO | SO |
|----------------------------|----|----|-----|----|
| Density at 20 °C, kg/m³    | 839| 914| 920 | 916|
| Kinematic viscosity, mm²/s at: | | | | |
| 20 °C                      | 3.8| 75.0| 65.2| 68.7|
| 40 °C                      | 3.3| 34.6| 30.7| 32.0|
| 100 °C                     | 2.5| 8.1 | 7.4 | 7.7 |
| Cetane number              | 45 | 36 | 34 | 33 |
| Autoignition temperature, °C| 280| 318| 320 | 321|
| Amount of air required to burn 1 kg of fuel, kg | 14.5| 11.9| 12.4| 12.4 |
| Lower calorific value, H₀, MJ/kg | 42.5| 37.3| 37.1| 37.0|
| Weight content, %          | C  | 87.0| 78.0| 77.6| 77.5|
|                           | H  | 13.0| 10.0| 11.5| 11.5 |
|                           | O  | 0   | 12.0| 10.9| 11.0 |

In order to assess the fuel flammability in the CC of a diesel engine and the dynamics of the
subsequent combustion process, various indicators are used: the cetane number (CN), the ignition delay
period τ₀, the maximum combustion pressure p₀, the maximum rate of pressure rise (dp/dq)max and the
average rate of pressure rise (dp/dq)ave during combustion (φ - crank angle), the ratio of pressure rise
during combustion λ=p₀/p₀ (p₀ - pressure at the end of the compression stroke), etc. [1, 3]. The most
important of these indicators is the CN of fuels. The higher the CN, the shorter the ignition delay period
and the more smoothly the fuel-air mixture burns.

CN is determined as the volume fraction of cetane (n-hexadecane C₁₆H₃₄, the CN of which is taken
as 100) mixed with α-methylnaphthalene (its CN is 0). By mixing these two components in different
proportions, it is necessary to obtain the mixture with the same ignition delay period as the test fuel
under the same conditions. The percentage of cetane in the mixture corresponds to the CN of the test
fuel. This procedure for determining the CN of vehicle fuel was adopted in the first version of ASTM
D613 issued in 1941. New versions of ASTM D613 (since 1962) do not use α-methylnaphthalene, but
2,2,4,4,6,8,8-heptamethylnonane that is sometimes called HMN or isocetane with a CN of 15. The
mixture of n-hexadecane and α-methylnaphthalene is still used in GOST 3122-67 (Diesel fuels. Method
for determining the cetane number). There were several reasons for excluding α-methylnaphthalene
from ASTM D613. First, it readily forms peroxides that change the CN of mixtures based on it. In
addition, α-methylnaphthalene has an unpleasant smell, possesses carcinogenic properties, and is
difficult to obtain in a pure form.
The objectives of the work are to study the flammability of different VOs in the combustion chamber of diesel engines, to determine the factors affecting the CN of VO, and to determine the most significant factors. The following eleven VOs were investigated: rapeseed oil (RO), sunflower oil (SuO), soybean oil (SO), safflower oil No. 1 (SaO1), safflower oil No. 2 with high oleic oil (SaO2), corn oil (CO), sesame oil (SeO), peanut oil (PO), linseed oil (LO), cotton oil (CoO), and crambe oil (CrO).

2. Results
VOs are 95% to 97% composed of triglycerides (esters of glycerol and fatty acids), as well as monoglycerides and diglycerides. Acylglycerides, in the same way, contain molecules of different fatty (carboxylic) acids that are associated with the molecule of glycerol \( \text{C}_6\text{H}_{12}\text{(OH)}_3 \). \[3, 14\]. The fatty acid composition of VO includes both unsaturated fatty acids (linoleic, oleic, linolenic acids) and saturated acids (palmitic, stearic, arachidic, myristic acids). Table 2 shows the fatty acid composition of VO studied in \[15, 16\]. The physicochemical properties of these VOs are given in Table 3.

### Table 2. Fatty acid composition of VOs

| Fatty acid, composition formula, conditional composition formula | RO (No.1) | SuO (No.2) | SO (No.3) | SaO1 (No.4) | SaO2 (No.5) | CO (No.6) | SeO (No.7) | PO (No.8) | LO (No.9) | CoO (No.10) | CrO (No.11) |
|---------------------------------------------------------------|-----------|------------|----------|-------------|-------------|----------|-----------|-----------|----------|------------|-----------|
| Saturated fatty acids | 0 0 0 0 0 0 0 0 0 0 0 0 | | | | | | | | | | | |
| Palmitic, \( \text{C}_{16}\text{H}_{32} \), C 16:0 | 3.49 6.08 11.75 8.60 5.46 11.67 13.10 11.38 4.92 28.33 2.07 | | | | | | | | | | | |
| Stearic, \( \text{C}_{18}\text{H}_{36} \), C 18:0 | 0.85 3.26 3.15 1.93 1.75 1.85 3.92 2.39 2.41 0.89 0.70 | | | | | | | | | | | |
| Arachidic, \( \text{C}_{20}\text{H}_{40} \), C 20:0 | 0 0 0 0 0 0.23 0.24 0 1.32 0 0 2.09 | | | | | | | | | | | |
| Behenic, \( \text{C}_{22}\text{H}_{44} \), C 22:0 | 0 0 0 0 0 0 2.52 0 0 0.80 | | | | | | | | | | | |
| Lignoceric, \( \text{C}_{24}\text{H}_{48} \), C 24:0 | 0 0 0 0 0 0 1.23 0 0 1.12 | | | | | | | | | | | |
| In total | 4.34 9.34 14.90 10.53 7.78 13.76 17.02 18.84 7.33 29.22 6.78 | | | | | | | | | | | |

### Table 3. Physicochemical properties of VOs

| Properties | RO (No.1) | SuO (No.2) | SO (No.3) | SaO1 (No.4) | SaO2 (No.5) | CO (No.6) | SeO (No.7) | PO (No.8) | LO (No.9) | CoO (No.10) | CrO (No.11) |
|-------------|-----------|------------|----------|-------------|-------------|----------|-----------|-----------|----------|------------|-----------|
| Density at 38 °C, kg/m³ | 911.5 916.1 913.8 914.4 902.1 909.5 913.3 902.6 923.6 914.8 904.4 | | | | | | | | | | | |
| Viscosity at 38 °C, mm²/s | 37.0 33.9 32.6 31.3 41.2 34.9 35.5 39.6 27.2 33.5 53.6 | | | | | | | | | | | |
| Cetane number | 37.6 37.1 37.9 41.3 49.1 37.6 40.2 41.8 34.6 41.8 44.6 | | | | | | | | | | | |
| Autoignition temperature, °C | 246 274 254 260 293 277 260 271 241 234 274 | | | | | | | | | | | |

The preliminary analysis of the data in Tables 2 and 3 showed that the CN (according to ASTM D613) of the studied VOs depends on their fatty acid composition, primarily on the content of saturated fatty acids and unsaturated oleic acid in VOs. Another factor affecting the flammability of VOs in the conditions of the CC of diesel engines, characterized by CN, is their flash point determined in accordance with ASTM D93. The methodology of this standard involves the determination of the flash point of petroleum products in a closed-cup in a temperature range from 40 to 360 °C by using a manual or automatic Pensky-Martens instrument. It is also possible to determine the flash point of biodiesel by this method, possessing fire safety with handling fuels.

One of the factors affecting the CN of VOs is the content of saturated fatty acids in them. This is due to the fact that saturated fatty acids have a relatively low autoignition temperature. The two most
important saturated fatty acids in VOs are palmitic and stearic acids (see Table 2). Their autoignition temperatures determined by GOST 12.1.044-89 (Fire and explosion safety of substances and materials) are 210 and 320 °C, respectively. However, the autoignition temperatures of linolenic and erucic fatty acids (unsaturated fatty acids) are 470 and 454 °C, respectively.

In order to estimate the relationship between the CN and the content of saturated fatty acids in VOs ($C_{SFA}$), the data in Tables 2 and 3 were used. Figure 1 shows the CN and the content of saturated fatty acids for nine VOs in Tables 2 and 3 (nine experimental points). However, the data for two VOs with abnormal content of unsaturated fatty acids were not used - high oleic SaO2 (No. 5) contains 79.36% of oleic acid, and high erucic CrO (No. 11) contains 58.51% of erucic acid (the content of this fatty acid for other VOs in Tables 2 and 3 is close to zero). With the use of the data in Figure 1 and the least square method, an approximation of the dependence $CN = f(C_{SFA})$ is carried out. The expression describes the fitted line plotted in Figure 1:

$$ECN = 23.55 \times C_{SFA} + 35.6,$$

where $ECN$ is the predicted cetane number.

![Figure 1. The relationship between CN and $C_{SFA}$](image)

The correlation coefficient between the CN of the studied VOs and $C_{SFA}$ was equal to $R = 0.69$ (the coefficient of determination - $R^2 = 0.48$), which indicates the presence of a correlation between CN and $C_{SFA}$.

Another factor affecting the CN of VOs is the content of oleic acid in them ($C_{OLA}$). Among the main unsaturated fatty acids composing vegetable oils, oleic acid has the lowest autoignition temperature. The autoignition temperature of oleic acid determined according to GOST 12.1.044-89 (Fire and explosion safety of substances and materials) is 271 °C. And the autoignition temperature of linolenic and erucic acids are 470 and 454 °C, respectively. The data for eight VO (No. 2-9 in Tables 2 and 3) were used to evaluate the correlation between the CN of VOs and $C_{OLA}$ shown in Figure 2. At the same time, the data for three VOs with abnormal content of saturated fatty acids were not used – RO (No. 1) with a minimum content of saturated fatty acids (4.34%) among the studied VOs, CoO (No. 10) with a maximum content of saturated fatty acids (29.22%), and CrO (No. 11) with an abnormal content of erucic acid (58.51%).

With the use of the data in Figure 2 and the least square method, an approximation of the dependence $CN = f(C_{OLA})$ is carried out. A linear relationship has been obtained as:

$$ECN = 15.34 \times C_{OLA} + 34.64.$$

The correlation analysis of CN= $f(C_{OLA})$ confirmed the presence of a fairly close correlation relationship between these parameters - the correlation coefficient between CN of the studied VOs and $C_{OLA}$ was $R = 0.81$ (coefficient of determination - $R^2 = 0.66$).
As a third parameter associated with the CN of the studied VO\(_s\), their flash point \((T\text{FP})\) in a closed-cup determined in accordance with ASTM D93 was taken into account. In order to analyze the relationship between the CN of VO\(_s\) and their \(T\text{FP}\), eight points corresponding to VO\(_s\) No. 1, 3-5, 7-9, and 11 in Table 2 and 3 were plotted in Figure 3. At the same time, data for VO\(_s\), which have an abnormal content of non-saturated fatty acids, were not used - SuO (No. 2) with a linoleic acid content of 73.73%, CO (No. 6) with a linoleic acid content of 60.60%, and CoO (No. 10) with a minimum content of unsaturated fatty acids equal to 70.78%.

Based on the data in Figure 3 and the least square method, an approximation of \(\text{CN} = f(T\text{FP})\) by a straight line was carried out. An analytical expression for \(\text{CN} = f(T\text{FP})\) has been obtained and has the following form:

\[
\text{ECN} = 0.2552 \times T\text{FP} - 25.88. \tag{3}
\]

By conducting a correlation analysis of \(\text{CN} = f(T\text{FP})\), the correlation coefficient of this dependence was obtained and equal to \(R = 0.96\) (the coefficient of determination - \(R^2 = 0.92\)). The high value of the correlation coefficient indicates a very close correlation relationship between the CN of VO\(_s\) and their flash point.

3. Discussion

A large number of works have been devoted to the problem of using various VO\(_s\) as additives to petroleum DF - there are more than 300 publications from 2015 to the present in the Scopus database [2]. The possibilities of using petroleum DF blended with various VO\(_s\) - RO, SuO, SO, palm oil, Jatropha oil, Castor oil, Karanja oil as diesel engine fuels were reviewed in [12]. The performance of a DI-diesel engine fueled with petroleum DF, RO, and RO methyl ester was investigated in [17]. The possibility of operating a diesel engine on petroleum DF blended with biofuels at a concentration from 0 to 100% has been analyzed. The possibility of using LO as an additive to petroleum DF was investigated in [18].
content of this additive was 30 and 50%. These publications indicate the urgency of studying the possibilities of using VOs as diesel engine fuels.

A number of publications [18, 19, 20] are devoted to analytical and experimental studies of the flammability of biofuels in the CC of diesel engines, including studies of the CN of biofuels, such as VOs.

The relationship between CN and the ignition delay $\tau_d$ in a constant volume combustion chamber was investigated for reference fuels (mixtures of hexadecane and 2,2,4,4,6,8,8-heptamethylnonane at different concentrations of these components) in [21]. The obtained relationship between CN and $\tau_d$ as determined in this chamber can be expressed as:

$$ECN = 38.07 \left( \tau_d - 0.35 \right)^{-0.6484}.$$ (4)

And then, Freedman et al. [21] measured the ignition delays of different triglycerides in this chamber and calculated their CN by formula (4), as shown in Table 4.

**Table 4.** Estimated cetane number of triglycerides in [21], derived cetane number of triglycerides, and constant $D$

| Conditional formula of triglycerides | Ignition delay, ms | Estimated cetane number | Derived cetane number |
|--------------------------------------|-------------------|-------------------------|-----------------------|
| TG 16:0                              | 1.96              | 89                      | 88.89                 |
| TG 18:0                              | 1.98              | 85                      | 85.02                 |
| TG 18:1                              | 2.45              | 45                      | 44.47                 |
| TG 18:2                              | 2.94              | 32                      | 34.22                 |
| TG 18:3                              | 3.85              | 23                      | 24.47                 |
| TG 21:1                              | -                 | -                       | 48.47                 |
| Non-basic triglycerides              |                   |                         |                       |
| TG 14:0, TG 20:0, TG 22:0, TG 24:0   | -                 | -                       | 84.03                 |
| constant $D$                          |                   |                         | -43.41                |

In order to predict CN of VOs based on the CN of triglycerides, a multi-factorial dependence of the CN of VOs on the content of basic triglycerides in them has been proposed. This relationship can be expressed by taking into account the contribution of the basic triglycerides:

$$ECN = \sum_i DCN_i \times C_i + DCN_0 \times C_0 + D \times C_{USA} \times C_{SA},$$ (5)

where $C_i$ is the concentration of the $i$-th basic triglyceride; $DCN_i$ is the derived CN of the $i$-th basic triglyceride; $C_0$ is the concentration of the group of non-basic triglycerides (i.e., triglycerides with fatty acids C 14:0, C 20:0, C 22:0, and C 24:0); $DCN_0$ is the derived CN of the group of non-basic triglycerides; $C_{USA}$ is the concentration of triglycerides with unsaturated fatty acids; $C_{SA}$ is the concentration of triglycerides with saturated fatty acids; $D$ is a constant. With the use of the least square method, the values of $DCN$ in this formula were calibrated for VOs No. 2-4, No. 7, No. 9, No. 10 (in Tables 2 and 3), containing only fatty acids C 16:0, C 18:0, C 18:1, C 18:2, and C 18:3. After that, the obtained $DCN$ for the basic triglycerides (except for TG 21:1) and the data on the fatty acid composition for all eleven VOs (Tables 2 and 3) were used to determine $DCN$ of TG 21:1, $DCN_0$ of the group of non-basic triglycerides and the constant $D$. The obtained values of these parameters are shown in Table 4.

The comparison of the CN of VOs calculated by the formula (5) with the experimental data in Tables 2 and 3 is shown in Figure 4.

Table 5 shows the regression parameters of the fitted dependences predicting CN in the study. The fitted dependence of the CN of VOs on their flash point in a closed-cup has the highest degree of fitting (prediction accuracy) - CN = $f(T_{FP})$ with a determination coefficient $R^2 = 0.92$. The dependence of the
CN on the content of oleic acid in VO has a relatively high prediction accuracy - $\text{CN} = f(C_{OA})$ with a determination coefficient $R^2 = 0.66$. The dependence of the CN on the content of saturated fatty acids in VO has the prediction accuracy - $\text{CN} = f(C_{SFA})$ with a determination coefficient $R^2 = 0.48$. The multi-factorial dependence of CN with the content of triglycerides in biofuel has a determination coefficient $R^2 = 0.53$. However, the multi-factorial dependence is more complicated to use than the other dependences predicting the CN of VOs.

| Table 5. Regression parameters of the dependences predicting CN |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Regression parameters       | Value                       |
| $\text{CN} = f(C_{SFA})$    | 0.48                        |
| $\text{CN} = f(C_{OA})$     | 0.66                        |
| $\text{CN} = f(T_{FP})$     | 0.92                        |
| $\text{CN} = f(C_i, C_0, C_{USA}, C_{SA})$ | 0.53 |
| Determination coefficient $R^2$ |                      |
| Maximum absolute deviation  | 3.22                        |
| Maximum relative deviation  | 11.84                       |
| $\Delta_{\text{max}}, \%$   | 5.71                        |
| Average absolute deviation  | 1.46                        |

**Figure 4.** The comparison of the CN calculated by the formula (5) (ordinate axis) with the experimental data in Tables 2 and 3 (abscissa axis).

4. Conclusion
One of the problems of using VOs as diesel engine fuels is their lower flammability compared to petroleum DF. The flammability indicators of vehicle fuels in the CC of diesel engines were considered. The most important among them is the CN. The dependences of the CN of VOs on their flash point in a closed-cup, the content of oleic acid, and saturated fatty acids in oils have been analyzed. Corresponding fitted expressions for these dependences have been obtained. Compared with the multi-factorial dependence of CN on the triglyceride contents, single-parameter dependences have the highest accuracy and convenience to use. The fitted dependence of CN on flash point has the highest prediction accuracy with a determination coefficient of 0.92. The dependence of the CN on the content of saturated fatty acids has the lowest prediction accuracy with a determination coefficient of 0.48.

References
[1] L’otko V, Lukalin V N and Khachiyan A S 2000 *The use of alternative fuels in internal combustion engines* (Moscow: MADI)
[2] Markov V A, Kamaldinov V G, Zykov S A and Sa B 2020 Optimization of the Composition of Blended Biodiesel Fuels with Additives of Vegetable Oils *Int. J. Energy a Clean Environ.* 20303–19
[3] Markov V A, Devyanin S N, Semenov V G, Bagrov V V and Zykov S A 2019 *Motor fuels produced from vegetable oils* ed V A Markov (Riga: Lambert Academic Publishing)
[4] Kamenev V F, Shatrov M G, Terrenchenko A С and Karpukhin K E 2014 *Thermal engines of electrical and heat supply installations using biofuels* (Moscow: MADI)
[5] Vallejo Maldonado P R 2008 *Energy-saving technologies and alternative energy* (Moscow:
Vasiliev I P 2009 *The influence of vegetable fuels on the environmental and economic performance of a diesel engine* (Lugansk: East Ukrainian National University named after V. Dahl)

Parsadanov I V 2003 *Improving the quality and competitiveness of diesel engines based on an integrated fuel and environmental criterion* (Kharkov: KhPI Publishing House)

Knothe G, Kralh J and Van Gerpen J 2015 *The biodiesel handbook* (Urbana: AOCS Press)

Myo T 2008 *The Effect of Fatty Acid Composition on the Combustion Characteristics of Biodiesel* (Japan: Kagoshima University)

Spessert B M, Arendt I and Schleicher A 2004 Influence of RME and Vegetable Oils on Exhaust Gas and Noise Emissions of Small Industrial Diesel Engines *SAE Tech. Pap.* 2004–32–0070

İlkiliç C and Yücesu H S 2005 Investigation of the effect of sunflower oil methyl ester on the performance of a diesel engine *Energy Sources* **27** 1225–34

Mat S C, Idroas M Y, Hamid M F and Zainal Z A 2018 Performance and emissions of straight vegetable oils and its blends as a fuel in diesel engine: A review *Renew. Sustain. Energy Rev.* **82** 808–23

Hazar H and Sevinc H 2019 Investigation of the effects of pre-heated linseed oil on performance and exhaust emission at a coated diesel engine *Renew. Energy* **130** 961–7

Alimentarius K 2007 *Fats, oils and derivatives* (Moscow: West World)

Goering C E and Daugherty M J 1982 Energy accounting for eleven vegetable oil fuels *Trans. ASAE* **25** 1209–15

Goering C E, Schwab A W, Daugherty M J, Pryde E H and Heakin A J 1982 Fuel properties of eleven vegetable oils *Trans. ASAE* **25** 1472–7

Raman L A, Deepanraj B, Rajakumar S and Sivasubramanian V 2019 Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel *Fuel* **246** 69–74

Velmurugan K and Gowthaman S 2012 Effect of cetane improver additives on emissions *Int. J. Mod. Eng. Res.* **2** 3372–5

Canoira L, Alcántara R, Torcal S, Tsiouvaras N, Lois E and Korres D M 2007 Nitration of biodiesel of waste oil: Nitrated biodiesel as a cetane number enhancer *Fuel* **86** 965–71

Tat M E 2011 Cetane number effect on the energetic and exergetic efficiency of a diesel engine fuelled with biodiesel *Fuel Process. Technol.* **92** 1311–21

Freedman B, Bagby M O, Callahan T J and Ryan III T W 1990 Cetane numbers of fatty esters, fatty alcohols and triglycerides determined in a constant volume combustion bomb *SAE Trans.* 153–61