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A note on the combustion of blends of diesel and soya, sunflower and rapeseed vegetable oils in a light boiler

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ABSTRACT

This paper deals with the study of the vegetable oils (VO) used as fuel for heating. The properties of sunflower, rape and soya oils are studied and these are compared with the properties of C-diesel fuel (used for heating domestic purposes in Spain). The mixtures of VO and diesel are studied and characterized and, finally, the results of a series of combustion trials of the mixtures in a conventional heating installation with a mechanical pulverization burner are presented. The results show that viscosity of VO limits the use of blends up to 40% of them, and the oxygen present in their structures contributes to an efficiency gain.

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1. Introduction

This paper only deals with the subject of oleaginous crops that can be grown in Spain, such as sunflower, rape and soya.

Nowadays, interest has grown in the use of vegetable oil (VO) as fuel. Those countries showing most interest in the use of these substances are the ones without petroleum resources and a strong agricultural potential.

Currently, there are three means of using these oils as a diesel substitute:

- VO, crude or refined;
- oils mixed with conventional diesel in different proportions; and
- products from the transesterification of VO with simple alcohols.

2. Oleaginous cultivation and biofuels

Biomass, which is solar energy stored in organic vegetable material by means of photosynthesis, can be used in two ways from the point of view of energy use [1,2]:

- Burning it to produce heat, which is the process that has been used throughout history.
- Transforming it first to fuel form, to be able to store it and transport it more easily before use, as in the extraction of oil.

One of the main advantages of VO is its life cycle, as it is a closed cycle. Crops take CO₂ via photosynthesis from the

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atmosphere. Oil is extracted from these crops which can be used directly as fuel or, after the pertinent transformations, a fuel can be obtained which, when burned, generates CO₂ that can be absorbed by the plants (Fig. 1).

- Environmental advantages of VO:
 - Total reduction of sulphur emissions
 - 50% reduction in CO emissions
 - 65% reduction in the emission of particles
 - 50% reduction in hydrocarbon emissions
 - Minor influence on the greenhouse effect when used instead of fossil fuels
- Energetic advantages of VO:
 - Renewable energy source
 - Reduction of the dependence on fossil fuels
 - Positive energy balance
- Socio-economic advantages of VO:
 - Use of marginal land for energy purposes
 - Maintains employment and income levels in rural areas
 - Avoids population migrations
 - Encourages job creation in various agro-industries
 - Contributes to the creation of new jobs
- Advantages of the use of mixtures for heating purposes:
 - The oil is obtained in conventional plants, with the resulting increase in production and profitability, in which case the price of VO could be controlled, as two different markets would exist.
 - The oils would be used in C-diesel installations, so investment is the same as for conventional fuels. The substitution percentage can vary up to a maximum of 40% of VO, thus permitting the installation to work continually, eliminating the temporal nature of biomass.
 - Oils have no storage problems, when they will be used as fuels.

The main disadvantage of the use of diesel/VO mixtures is that they can only be applied to oleaginous crop plants.

3. Sunflower oil

The different varieties of sunflower used to obtain oil have widely differing oil contents. On average, every 100 kg of sunflower seeds give between 60 and 70 kg of kernels, the average oil content of each kernel being from 45% to 57%.

The chemical composition of sunflower oil is shown in Table 1.

4. Rapeseed oil

The use of rape in diesel motors causes problems with low percentage mixtures in continuous regime [11]. However, using rape in heating systems does not give rise to problems due to the simplicity of the burners for liquid fuel.

The characteristics of rapeseed vegetable oil are shown in Table 2.

5. Soya oil

Soya, due to its large production and low prices, is the first candidate for mixing with diesel as fuel [7].

The use of pure soya oil with diesel cannot be recommended in the long term in diesel engines due to the accumulation of carbon deposits which can lead to problems [7].

Faletti studied the percentage of heat from the emissions of hybrid soya oil fuels to determine why they are more heat efficient than diesel fuels. The soya oil hybrid fuel showed a

Table 1 – Chemical composition of sunflower oil (*Helianthus annuus*) [3,4]

Type	Refined (%)	Crude (%)
Peroxides	0.06	2.86
Humidity %	*	0.18
Phosphates	Unappreciable	*
C 14:0	0.06	0.06
C 16:0	6.22	6.22
C 16:1	0.10	0.10
C 18:1	22.25	22.25
C 18:2	65.12	65.12
C 18:3	0.08	0.08
C 20:0	0.32	0.32
C 20:1	0.15	0.15
C 22:0	0.79	0.79
C 22:1	0	0
C 24:0	0.24	0.25

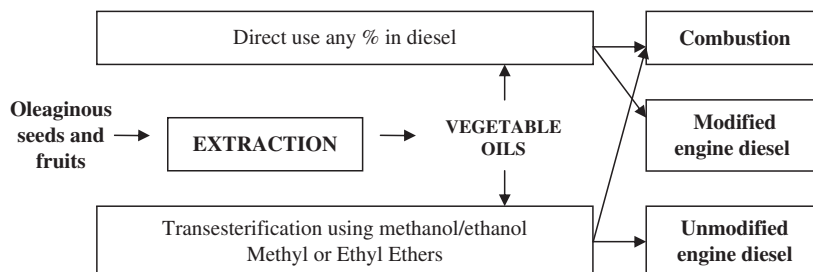


Fig. 1 – Oleaginous seeds and fruits.

Table 2 – Chemical composition of refined and crude rapeseed oil (*Brassica napus*) [5,6]

Type	Refined (%)	Crude (%)
Peroxides	0.08	0.85
Humidity %	*	0.16
Phosphates	Unappreciable	*
C 14:0	0.06	0.05
C 16:0	4.72	4.32
C 16:1	0.24	0.23
C 18:0	2.49	1.98
C 18:1	54.62	80.27
C 18:2	27.20	19.58
C 18:3	7.14	9.19
C 20:0	0.58	0.68
C 20:1	1.27	1.64
C 22:0	0.42	0.36
C 22:1	0.58	0.77
C 24:0	0.16	0.14

Table 3 – Chemical composition of refined and crude sunflower oil (*Soja hispida*) [9]

Type	Crude (%)	Refined (%)
Peroxides	0.85	0.05
Humidity %	0.21	*
Phosphates	*	Unappreciable
C 14:0	0.07	0.07
C 16:0	10.90	10.63
C 16:1	0.07	0.06
C 18:0	4.08	4.62
C 18:1	21.77	23.17
C 18:2	54.43	52.47
C 18:3	6.81	6.77
C 20:0	0.46	0.50
C 20:1	0.22	0.34
C 22:0	0.54	0.52
C 22:1	0	0
C 24:0	0.18	0.18

longer delay in the ignition than for diesel C, and this gives it a greater efficiency in combustion processes than diesel [8].

Characteristics of soya VO are shown in Table 3.

As can be seen in the table of characteristics for rape and soya oils, the difference in the percentage of molecules of a different length would seem to indicate a greater density for soya than for rape.

6. Comparison of vegetable oils with hydrocarbons

The structure of VO, its methyl ethers and hydrocarbons is fairly similar. They all have a hydrocarbon chain except the functional groups belonging to the esters in the case of VO and its esters.

Supposing a length equal to the hydrocarbon chain in all three cases, both the density and the viscosity will be greater

for the oil, because of their three functional groups. The VO are followed by their methyl esters and finally the hydrocarbons, whose structure means that the intermolecular unions will be the weakest of the three, thus having the lowest density and viscosity. Within each group, an increase in the length of the chain would bring with it an increase in the density and the viscosity; so, from the structure, it is possible to deduce the properties.

The current intention is to adapt the new fuels as far as possible to already existing motors and boilers, the priority being to ascertain the physical and chemical characteristics of these products for their adequate use.

Table 4 shows a comparison between the most important characteristics of diesel and VO, and it is useful to compare VO used as fuel with diesel, as can be seen in Table 5 [1]. If we look carefully at the table, the greatest differences can be seen between the oils and the diesels, and this indicates the problematic points that can be found on using oils (or mixtures) where only C-diesel is normally used. The most critical differences are the viscosities. This indicates that a mixture with a high percentage of oil could probably not be used, as the high viscosity can cause problems in the pump, unless the fuel is heated to a temperature at which the viscosity is within the recommended limits. Supposing a constant volumetric flow of fuel, a high density can also be observed, higher than that of pure C-diesel, and this would in part compensate for the lower calorific value of the fuel. The mixture, on burning, gives off less calorific energy, but if a greater quantity is burnt, this effect can be neutralized.

In the following, we set out the characteristics of each of the mixtures of VO and diesel under study.

7. Analysis of vegetable oil–diesel mixtures

7.1. Mixtures of sunflower oil and diesel

Increasing the oil content in the mixture increases the density as the structure of the oil has a greater polarity than the hydrocarbons present in diesel, which brings about a greater effect in the molecular aggregation. As for the composition of the mixture, the percentage of hydrogen and

Table 4 – Comparison between diesel and oil

Property	Diesel	Vegetable oils
Distillation interval		The final distillation temperature is very high, so most of it decomposes before reaching distillation temperature
Calorific value (MJ kg ⁻¹)	2.464	2.153
Cetane rating (autoinflammability)	40	> 45
Density at 15 °C (kg m ⁻³)	680–810	910–940
Viscosity (cSt)	2.70	32.60

Table 5 – Physical and chemical properties of VO and C-diesel

	Sunflower	Soya	Rape	C-diesel
Density at 15 °C (kg m ⁻³)	923	923	921	848
Density at 35 °C (kg m ⁻³)	912	911	909	635
Viscosity at 40 °C (cSt)	32.6	32.9	35.1	2.7
Viscosity at 100 °C (cSt)	7.7	7.6	8.1	1.2
S (mass%)	0.03	0.06	0.03	0.07
C (mass%)	79.3	79	79.6	86.6
H (mass%)	11.1	11.2	11.4	12.3
O (mass%)	9.57	9.74	8.97	1.03
HHV (kJ kg ⁻¹)	2252	2243	2246	2568
LHV (kJ kg ⁻¹)	2117	2107	2108	2419

Table 6 – Characteristics of the sunflower oil (*Helianthus annuus*) and diesel oil mixtures [10]

Sample	VO (vol%)	Density at 15 °C (kg m ⁻³)	Viscosity (cSt)	%C (kg kg ⁻¹)	%H (kg kg ⁻¹)	%O (kg kg ⁻¹)	%S (kg kg ⁻¹)	LHV (kJ kg ⁻¹)
G-0	0	848.00	2.70	86.60	12.30	0.90	0.20	2561
G-10	10	856.16	3.60	85.81	12.18	1.83	0.18	2556
G-20	20	864.33	4.50	85.01	12.06	2.77	0.16	2515
G-30	30	872.49	5.80	84.22	11.94	3.70	0.14	2472
G-40	40	880.65	7.40	83.42	11.82	4.63	0.13	2445
G-50	50	888.82	9.50	82.63	11.70	5.56	0.11	2417
G-60	60	896.98	12.30	81.83	11.58	6.50	0.09	2379
G-70	70	905.14	15.40	81.04	11.46	7.43	0.07	2347
G-80	80	913.31	20.10	80.24	11.34	8.36	0.05	2178
G-90	90	921.47	25.90	79.45	11.22	9.30	0.03	2279
G-100	100	923.00	32.60	79.30	11.20	9.47	0.03	2117

carbon decreases while that of oxygen increases. This is because, on increasing the amount of oil, carboxyl groups, that contain this element, are being added.

With the decrease in hydrogen and carbon per kg of fuel, the LHV decreases, which means that the calorific value of the fuel is lower.

Table 6 shows the characteristics of the mixtures obtained by means of the weighted calculation of the characteristics of the refined sunflower oil and the C-diesel, both pure.

The viscosity values were found experimentally in the laboratory [8].

It can be seen that the viscosity increases with the quantity of oil in the mixture. This is a problem because the viscosity of the fuel has a maximum which will depend on the installation in which the combustion will take place.

7.2. Mixtures of rape oil and diesel

The mixture with diesel is carried out to decrease the oil's viscosity. This can clearly be seen in the graph as C-0 has a viscosity much lower than C-100, which is the one that has 100% rapeseed oil.

The physical properties of the mixtures of C-diesel and rapeseed oil are described in Table 7 [5].

According to the data in Table 8, there is an increase in the viscosity in line with the increase in the proportion of

rapeseed oil. Since conventional C-diesel installations function with a pressurized mechanical pulverization burner, this technology is limited to a viscosity of 10 cSt at 20 °C, so the valid mixtures are those with percentages under 30% of rapeseed oil.

7.3. Mixtures of soya oil and diesel

The mixtures used as fuels were made in volumetric percentages. Thus, and to facilitate understanding, from now on, we shall speak of an S-10 mixture, meaning that is a mixture of 90% C-diesel and 10% refined soya oil, and so on for S-20, S-30, etc. S-0 indicates pure C-diesel. The same applies for mixtures containing sunflower oil (G), as well as for rapeseed oil (C).

This section studies the different characteristics of the refined soya oil and its mixtures with C-diesel, so as to be able to predict their optimum behaviour as fuels. The characteristics of the mixtures are determined from either: (i) other known properties (derivatives) or (ii) the knowledge of the said properties in the pure components that make up the mixture (theoretical) or (iii) laboratory measurements (empirical).

Table 8 shows the density at 15 °C, the LHV of mixtures of soya oil and C-diesel, obtained empirically.

Table 7 – Characteristics of rapeseed oil (*Brassica napus*) and diesel oil mixtures

Sample	VO (vol%)	Density at 15 °C (kg m ⁻³)	Viscosity (cSt)	%C (kg kg ⁻¹)	%H (kg kg ⁻¹)	%O (kg kg ⁻¹)	%S (kg kg ⁻¹)	LHV (kJ kg ⁻¹)
C-0	0	848	2.7	86.60	12.30	0.99	0.11	2419
C-10	10	855	3.6	84.70	12.50	2.68	0.12	2386
C-20	20	864	4.7	84.80	12.50	2.58	0.11	2354
C-30	30	872	5.9	84.40	12.30	3.20	0.10	2321
C-40	40	880	7.72	83.00	12.00	4.92	0.08	2288
C-50	50	888	10.2	82.40	12.10	5.46	0.04	2255
C-60	60	896	13	80.90	12.00	7.06	0.04	2222
C-70	70	904	16.8	81.30	11.70	6.97	0.03	2189
C-80	80	912	21.1	80.30	11.70	7.98	0.02	2156
C-90	90	920	27.5	80.50	11.60	7.88	0.02	2124
C-100	100	921	35.1	79.60	11.40	8.97	0.03	2117

Table 8 – Characteristics of the sunflower oil (*Soja hispida*) and diesel oil mixtures

Sample	VO (vol%)	Density at 15 °C (kg m ⁻³)	Viscosity (cSt)	%C (kg kg ⁻¹)	%H (kg kg ⁻¹)	%O (kg kg ⁻¹)	%S (kg kg ⁻¹)	LHV (kJ kg ⁻¹)
S-0	0	848	2.7	86.6	12.3	0.99	0.11	2431
S-10	10	858	3.1	84.6	12.3	2.91	0.15	2397
S-20	20	865	4	84.7	12.3	2.82	0.14	2364
S-30	30	872	5.1	83.8	12.1	3.97	0.13	2331
S-40	40	880	6.72	83.0	11.9	5.00	0.10	2299
S-50	50	887	9.5	82.2	12.0	5.74	0.06	2268
S-60	60	894	12.1	80.4	11.8	7.75	0.05	2237
S-70	70	901	15.4	80.5	11.7	7.75	0.05	2206
S-80	80	908	19.7	79.8	11.5	8.64	0.06	2176
S-90	90	916	25.3	79.9	11.3	8.75	0.05	2146
S-100	100	923	32.9	79.0	11.2	9.74	0.06	2117

Table 9 – Characteristics of the generating energy group used in the combustion tests

Boiler model AR/25GT by ROCA	
Boiler type	Cast iron
Calorific power (kW)	26.7
Water capacity (dm ³)	26
Approximate weight (kg)	210
Maximum working temperature (°C)	110
Burner model KADET-TRONIC by ROCA	
GPH nozzle	0.6
Angle (°)	60
Pump pressure (MPa)	0.8–1.6
Flow (dm ³ h ⁻¹)	2.3
Regulation of air (%)	40–70–100

Table 10 – Control parameters for the installation

T _{input} (°C)	Water temperature in the distributor situated in the input circuit
T _{returning} (°C)	Water temperature in the return tank, through which all the water flows before returning to the boiler
P _{impulse} (MPa)	Water pressure in the main circuit impulse, just before the distributor
P _{aspiration} (MPa)	Water pressure in the aspiration of the water pump situated before the entry to the distributor
P _{impulse fuel} (MPa)	Impulse pressure in the fuel pump
P _{aspiration fuel} (mmHg)	Aspiration pressure in the fuel pump
T _{fuel} (°C)	Temperature of the fuel situated in the tank
T _{boiler} (°C)	Temperature of the water passing through the boiler
T _{ambient} (°C)	Room temperature

8. Experimental installation and measuring apparatus

The energy-generating group is made up of a conventional house-heating boiler and burner, whose characteristics are shown in Table 9.

The control parameters of the installation are indicated in Table 10. These values should be maintained within a certain range for the experiment in order to be considered stationary.

The characteristics of the drills used to measure the combustion conditions are shown in Table 11.

Table 11 – Measuring equipment used in the experimental part, with their range of measurement

Fumes analyser (one piece)	
Make and model	TESTO model 342-3
K type thermometer	Range: 40–1200 ± 0.1 °C
Electrochemical O ₂ probe	Range: 0–21%
CO drill (with H compensation)	Range: 0–4000 ppm
NO electrolytic cell probe	Range: 0–3000 ppm
Temperature probe (five measurements)	
Thermopar type	K
Measurement range	–40 to 1000 ± 0.5 °C
Pressure probe (four measurements)	
Manometer type	Spiral
Impulse pressure range	0.1–4 MPa (accuracy to 1%)
Aspiration pressure range	0.02–0.1 MPa (accuracy to 1%)

9. Combustion analysis

On the basis of several studies and essays already carried out, it could be said that, as the quantity of oil in the mixture increases, the maximum quantity of carbon dioxide also increases, while the quantity of air needed decreases. The fact that the amount of air entering the combustion chamber is less has a positive effect on the performance of the combustion. Less air needs to be taken to flame temperature, and therefore less will be expelled at a certain thermal level via the chimney. If the temperature of the fumes can be kept within a narrow margin, the combustion of different mixtures can be compared.

Thus, it can be concluded that the performance of the combustion increases along with the content of oil in the fuel. Fundamentally, this is due to the decrease in the loss of

Table 12 – Experimental data of the combustion properties for oil/diesel mixtures

Sample	Pressure (MPa)	Regulation of air ^a (%)	CO ₂ (%)	CO (ppm)	NO (ppm)	Performance (%)
S-0	1.0	40	4.57	74.67	25.33	83.27
S-0	1.2	40	4.70	49.33	31.67	83.36
S-0	1.2	60	4.17	200.67	27.33	76.45
S-0	1.4	40	4.83	91.00	33.67	82.44
S-0	1.4	60	4.30	80.67	36.67	77.64
S-10	1.0	40	4.27	253.33	17.67	81.47
S-10	1.2	40	4.73	96.67	28.33	82.85
S-10	1.4	40	5.23	79.67	33.00	83.51
S-10	1.4	60	4.00	102.00	27.67	76.88
S-20	1.0	40	4.53	200.33	22.00	82.41
S-20	1.2	40	4.90	85.67	25.33	83.82
S-20	1.2	60	3.60	262.00	15.67	75.84
S-20	1.4	40	5.30	105.33	31.00	83.99
S-20	1.4	60	4.13	53.00	26.33	78.38
S-30	1.0	60	4.87	16.67	0.00	76.04
S-30	1.2	60	5.13	8.33	29.33	80.40
S-30	1.4	60	5.73	14.00	36.00	79.22
S-40	1.0	60	5.10	4.33	30.67	76.73
S-40	1.2	60	5.53	3.33	36.67	77.57
S-40	1.4	60	6.03	0.00	40.33	79.14
C-10	1.0	40	4.66	12.66	35.00	77.69
C-10	1.2	40	4.83	5.66	40.00	77.49
C-10	1.2	60	4.53	10	40.00	75.43
C-10	1.4	40	5.23	11.66	36.67	78.21
C-10	1.4	60	4.76	3	34.67	75.72
C-20	1.0	40	4.87	28.33	35.33	77.65
C-20	1.2	40	4.97	6	37.67	76.99
C-20	1.4	40	5.20	5	35.33	76.10
C-30	1.0	40	4.77	58.33	30.67	76.40
C-30	1.0	60	4.63	199.66	34.00	75.01
C-30	1.2	40	5.20	6.33	37.33	78.95
C-30	1.2	60	4.80	22.33	37.33	76.12
C-30	1.4	40	5.60	6.33	39.67	78.43
C-30	1.4	60	5.23	5	43.00	75.81
G-10	1.4	40	6.00	60.86	27.43	81.26
G-20	1.4	40	6.70	26.93	51.93	83.96
G-30	1.4	40	7.08	14.20	52.80	84.56
G-40	1.4	40	7.46	18.20	52.40	85.28
G-50	1.4	40	7.78	17.67	52.83	85.55

^a Air excess.

fumes, since the volume of air exiting through the chimney is less. Furthermore, as the evacuation temperature of the fumes is the same for all the mixtures, the less the air that comes out of the chimney, the smaller will be the energy loss.

If the combustion performance value is multiplied by the LHV of the fuel, the result is an improvement in the energetic efficiency, quite apart from the environmental question [9].

10. Characteristics of the combustion

The air minimum reflects the need of oxygen per kilogram of fuel; so a low value determines a lower calorific value, although it is probable that, in the combustion, there can be improvements in the performance because the mass of air that is needed to heat to flame temperature is less, as will be the heat expelled by the exhaust fumes. The $CO_{2\max}$ shows the amount of carbon the fuel has in relation to that of hydrogen. A greater percentage of $CO_{2\max}$ indicates a lower quantity of water and thus less fuel, and this in turn indicates a lower calorific value.

One can deduce that the air minimum will decrease along with the increase of oil in the mixture, as the concentration of oxygen increases. The $CO_{2\max}$ will increase as the hydrogen and carbon decrease. This can be seen in Table 12 [9].

The characteristic combustion parameters of VO and C-diesel mixtures obtained in the tests carried out in the previously described installation are shown in Table 12.

11. Conclusions

VO are one of the possible solutions nowadays, for the problem of the increase in CO_2 emissions deriving from the burning of fossil fuels. Combustion produces CO_2 , but when a fuel of vegetable origin is burnt, the carbon dioxide produced is compensated for that absorbed by the plants in the process of photosynthesis; it is a closed cycle.

VO are fuels with good performance levels, but their high viscosity is a problem when used in a pure state. They can be used in both motors and heating boilers, the latter being the less problematic application.

Their calorific value is close to that of diesels but the viscosity is 10 times higher. This is why mixtures of up to 40% oil are used to diminish the viscosity.

Another way to decrease the viscosity is through the reaction of transesterification, obtaining methyl and ethyl ethers with good properties, as it decreases the viscosity while maintaining the cetane rating. However, transesterifi-

cated products are not recommended for use in burners as they need to be submitted to a transformation which makes the product more expensive. The most interesting aspect is the use of mixtures with diesel, as neither the installations nor the oils need to be modified.

The advantages of using these fuels are several, since, besides reducing emissions and the dependence on fossil fuels, new jobs can be created taking advantage of marginal land for energy crops.

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