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Study on the Performance and Emissions of Triple Blends of Diesel/Waste Plastic Oil/Vegetable Oil in a Diesel Engine: Advancing Eco-Friendly Solutions

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Abstract: To provide technical and economical solutions regarding management of plastic waste, which is constantly increasing worldwide, this study addresses the possibility of using plastic oils (PO) obtained from these plastic wastes as biofuels. To this end, the replacement of the fossil diesel employed in internal combustion diesel engines with triple diesel/PO/vegetable oil mixtures has been investigated. Sunflower (SO) and castor oil (CO) mixed with PO in the most appropriate proportion are evaluated as pure vegetable oils (SVO). Thus, diesel/PO/SVO triple blends were prepared, characterized, and then tested on a diesel engine operating as electricity generator, evaluating power output, consumption, and exhaust emissions. The obtained results show that, with the incorporation of relatively small quantities of pure, non-edible vegetable oils, in double mixtures of PO/SO and PO/CO, an effective alternative fuel for transport is obtained, that allows for 100% of fossil diesel to be replaced. In fact, with these double PO/SVO biofuel mixtures, higher engine power values and lower consumption levels are obtained than those achieved with fossil diesel. Regarding exhaust emissions, these are produced with a slightly greater opacity than with fossil diesel, but there are lower values of carbon gases as a whole ($CO + CO_2$) and in NO_x gases.

Keywords: plastic oil; straight vegetable oils (SVO); castor oil (CO); sunflower oil (SO); biofuel; diesel engine; electricity generator; exhaust emissions; smoke opacity; Bosch smoke number

1. Introduction

Plastics are essential materials for people's way of life at present, since they are used in a wide variety of industrial and domestic applications. These materials are obtained from very different petroleum derivatives, so in addition to their non-renewable nature, they represent a great danger to the environment. This implies the need to obtain an adequate method for the elimination of waste plastics, which, after their useful life cycle, amount to 300 million metric tons annually over the world [1–3]. This is associated with important health and environmental problems at a global scale [4–6]. Therefore, it is essential to urgently develop adequate green techniques to recycle these plastic wastes into usable products in a circular economy scheme. In this sense, the application of these wastes in road construction or as a component in building materials has been described [7]. However, the transformation of plastic wastes into liquid final products through pyrolysis seems to be the most economically viable and environmentally friendly process of elimination, because these can be used as renewable fuels [8].

A process of replacing fossil fuels with others of a renewable nature is currently underway, with the aim of achieving a reduction in greenhouse gas emissions in the coming decades. At the end of this process, it is expected that thermal engines will

play a very reduced role compared to what they currently play in different means of transport, including cars, trucks, boats, and airplanes. However, the transition from the current transportation energy sources to new technologies based on electric motors will take several decades, during which electric vehicles and others that use combustion engines that use very low-emission fuels will coexist [9]. In this regard, renewable fuels research must remain especially active, especially considering the enormous number of cars that are currently being used worldwide with engines powered by fossil fuels. Therefore, research into alternatives needs to remain active for a long enough period of time to establish a replacement. In this sense, the enormous number of resources that will need to be incorporated into renewable fuels opens a window of opportunity for liquid products obtained through the pyrolysis of waste plastics, as, although these products are derived from non-renewable petroleum products, because they are obtained from wastes compounds, they have a renewable character [10].

To date, very diverse studies have been described in which liquid plastic oils operate properly, either as pure fuels or in mixtures with gasoline [11], kerosene [12] or diesel [13]. These studies demonstrate the great versatility of these products, which are capable of replacing a significant proportion of fossil fuels. This fact should drive the adoption of plastic-recycling measures worldwide, given the growing amount of these products, which are polluting the seas and rivers. Another possible application of the liquid fuels obtained by the pyrolysis of waste plastics could be their use in mixtures with straight vegetable oils (SVOs), for use in the compression–ignition (CI) diesel engines of current car fleets. SVOs cannot be employed in CI engines because they surpass the kinematic viscosity of fossil diesel [8]. For this reason, although SVOs exhibit physicochemical properties that are very similar to fossil diesel, they require pre-treatment to acquire the viscosity levels established by the European Regulation EN 590:2022 [14] before their use in CI engines.

To date, the reduction in the viscosity of different SVOs has been the main problem regarding their application in the current fleet of vehicles that operate with CI engines, given the limitations associated with the economic infeasibility of the process when aiming to produce biodiesel at a commercial level [15]. For this reason, in the fleet of diesel engines, there is currently a great delay in the process of replacing fossil fuels with biodiesel compared to gasoline engines operated with bioethanol as a biofuel. For this reason, in recent years, research has aimed to find a means of transforming SVO into biofuels in a technically and economically viable way [16]. At present, the most appropriate process is to obtain the so-called advanced biofuel, or "green diesel", that can be attained via the application of several catalytic processes (cracking or pyrolysis, hydrodeoxygenation, and hydrotreating) to the triglycerides, producing renewable diesel fuels that are very close to fossil fuels. Through these thermal treatments of the SVOs, completely deoxygenated fuels are obtained, with similar rheological properties to the paraffins that make up fossil diesel, which behave like fossil diesel, but provide a significant reduction in greenhouse gas emissions [17–20].

Another alternative to the use of SVOs as a fuel in current diesel engines consists of reducing the high viscosity of the plant oils by mixing these oils with low-viscosity organic solvents in appropriate proportions. This procedure, in principle, presents great economic advantages, since it avoids the use of any chemical process. However, these organic solvents, with lower viscosity values and a relatively short carbon chain, have a low energy density and, sometimes, a low cetane number, so their efficiency is slightly reduced compared to fossil diesel. These biofuels provide advantageous techno-economic conditions, since their cost is limited to that of the used oil and the corresponding organic solvent used in the blend. They are usually named low-viscosity low-cetane (LVLC) fuels [21–23].

The reduced economic cost of using a simple mixture of renewable organic compounds, instead of a biofuel obtained through any type of chemical treatment, such as pyrolysis, deoxygenation, or hydrotreatment of the SVO, has increased the interest in this methodology in recent years. Overall, a slight reduction in the power of conventional diesel

engines that are currently in use is obtained, with a consequent increase in the volume of fuel consumed. This, in turn, is accompanied by a significant reduction in polluting emissions. This has been confirmed by the high number of triple mixtures obtained with diesel using many SVOs and various low-viscosity organic solvents [24–30]. Thus, so far, SVOs using palm oil [24–26], castor oil [27], cashew nutshell oil [28], cotton seed oil [29], wheat germ oil [30], neem, and wintergreen oil have been evaluated [31]. Various LVLC solvents have been described, with various renewable organic compounds of low molecular weight, such as Melaleuca Cajuputi oil, [24–26], pine oil [27,30], camphor oil [28], orange oil or diethyl ether (DEE) [29], hexanol, and octanol [31].

Likewise, several renewable lightweight alcohols are also being studied as solvents to allow for the use of several pure vegetable oils in suitable mixtures to achieve viscosity values in the 2.0–4.5 cSt range, as imposed by the EN 590:2022 standard. This would allow for their use in conventional diesel engines. Thus, butanol has been investigated in triple blends with diesel fossil and different SVOs, such as croton oil [32], with canola/hazelnut/cottonseed oil blends and sunflower/corn/soybean oil blends [33], along with canola oil, soybean oil, sunflower oil, corn oil, olive oil, and hazelnut oil [34], neat cotton oil [35–39], palm fatty acid distillate [40], rapeseed oil [41], and jojoba oil [42,43]. Other alcohols are also being evaluated as LVLCs in triple blends, although butanol has attracted the most interest so far [39,44,45]. There have some studies on the use of ethanol [46], propanol [39,47], pentanol [31,39,44,45,47], hexanol, [31,48,49], and octanol [48]. Among the great proliferation of research aiming to achieve efficient, economical, and renewable LVLC solvents, diethyl ether (DEE) is one of the most studied materials, with different SVOs, such as cashew nutshell oil [50,51], neat cottonseed oil [29], bael oil [52–54], aegle marmelos oil [55,56], karanja oil [57], sunflower oil, and castor oil [58].

Sunflower oil and castor oil have also been recently evaluated as components of triple-diesel mixtures with different LVLC additives in triple D/LVLC/SVO mixtures. Hence, several LVLC solvents have been also investigated, including ethyl acetate [59], diethyl carbonate [60], dimethyl carbonate [61], acetone [62], and even a relatively low-cost mixture, acetone/butanol/ethanol (ABE), which can be derived from renewable resources through typical fermentation processes using cellulose found in various residual biomasses [63]. ABE blends demonstrate favorable physicochemical properties for use as an LVLC in biofuels [64–67].

In general, with all the organic compounds that have been investigated to date, such as LVLC in triple diesel/LVLC/SVO mixtures, slightly lower energy values are obtained due to the lower calorific values of the oxygenated compounds compared to hydrocarbons of similar molecular weights. Regarding the emissions of polluting gases, soot, nitrogen oxides (NO_x), and carbon dioxide (CO_2) are generally reduced, while CO emissions tend to increase. In general, the use of these oxygenated organic compounds as LVLC biofuels in mixtures with SVOs allows for high percentages of diesel to be obtained without seriously compromising the power of the engine, achieving a significant reduction in polluting emissions. Furthermore, the cold flow properties of the fuel mixtures were also improved with these kinds of blends [59–63]. In order to increase the energy performance of triple blends, various investigations have been carried out using a cetane improver such as 2-Ethylhexyl nitrate. In triple blends with diesel, hazelnut oil, and n-butanol or n-pentanol, the cetane number increased by 13.12% and 12.26% respectively, while it did not have any significant effect on the density, kinematic viscosity, cloud point, cold filter plugging point, or flash point [68]. In a triple diesel/peppermint biooil/DEE mixture, the presence of di-tertiary butyl peroxide (DTBP) as a cetane improver increases engine performance and reduces CO, HC, and smoke emissions [69].

However, with the investigated oxygenated fuels, a lower substitution power is achieved than when using gasoline as an LVLC solvent. Therefore, triple blends constituting diesel/gasoline/SVO achieved an up to 40% substitution of fossil diesel, demonstrating an excellent power performance and fuel efficiency compared to fossil diesel. Additionally, there was a notable decrease in pollutant emissions [70]. This is why, as the plastic oils

obtained by the thermal treatment of plastic waste of various origins are essentially composed of a mixture of hydrocarbons, like those found in fossil fuels, they could play a role as LVLC solvents in triples blends, with diesel and different SVOs. In this way, recycled organic material could be efficiently used, an essential objective when aiming to obtain advanced biofuel. In this respect, waste plastic solids are currently receiving renewed interest for use as an alternate fuel in a DI diesel engine, without any modification. The experimental results showed a stable performance with a thermal efficiency like that of fossil diesel. The amounts of toxic gas carbon-monoxide emissions, carbon dioxide, and unburned hydrocarbon were slightly higher than those obtained using diesel; however, smoke was reduced by about 40–50% in waste plastic oil [71]. Therefore, multiple studies have been described that evaluate its usefulness as an alternative, non-biodegradable, and renewable fuel, both alone and in different mixtures with organic solvents [72–77] or with biodiesel [78–81].

In this study, plastic oils are evaluated as an LVLC that could replace fossil diesel fuel with a renewable biofuel, obtained by mixing different quantities of materials considered renewable with commercially available vegetable oils, without competing with their use in food. Currently, the only vegetable oils available at an industrial scale without competing with their uses as a food are castor oil and waste cooking oil. Castor oil is the only inedible vegetable oil available at an industrial scale, which is currently used for several purposes, such as lubricants, paints, and pharmacy industries [82]. Therefore, this is the only oil that could be widely and immediately applied as a biofuel. Instead of using used cooking oil, sunflower oil has been studied as a standard to avoid the foreseeable changes due to the used oils having different origins.

This methodology could allow for high levels of fossil fuel substitution in a technically and economically viable way, because the technical process is reduced to the preparation of the best blends of the available vegetable oils with an appropriate amount of plastic oil as the LVLC solvent.

2. Materials and Methods

2.1. Preparation of Plastic Oil/SVOs Double Blends, and Diesel/Plastic Oil/SVOs Triple Blends

The plastic oil (PO) was supplied by the company Ecoan, based in Espiel (Córdoba), which markets a second-generation synthetic fuel for diesel engines, obtained from the continuous pyrolysis of wastes plastics. Sunflower oil (food grade) (SO) was obtained from a local market, and castor oil (CO) from Panreac, Castellar Del Valles, Spain. Both SVOs were mixed with a standard plastic oil LVLC solvent, at different concentrations, to obtain the optimum PO/SVO double blends that meet the rheological properties required by European diesel standard EN 590:2022. The fossil diesel used in the different triple blends was obtained in a Repsol service station. The most characteristic physicochemical properties of diesel oil, sunflower oil, castor oil, and plastic oil are shown in Table 1.

Table 1. The physicochemical properties of the different compounds were taken from the literature [58–63], except the density and kinematic viscosity, which were determined experimentally in this research. Flash point, calorific value and cetane number of the plastic oils are reported by [74,83,84].

Property	Diesel	Sunflower Oil	Castor Oil	Plastic Oil
Density at 15 °C (kg/m^3)	820	920	962	1045
Kinematic viscosity at 40 °C (cSt) [1]	3.20 ± 0.03	37.80 ± 0.46	226.20 ± 0.55	2.47 ± 0.01
Calorific value (MJ/kg)	35.1	34.3	35.5	42.0
Flash point (°C)	66	220	228	15
Auto-ignition temperature (°C)	250	316	448	261
Cetane number	50	37	40	60–71

[1] Viscosity value errors were obtained from an average of three measurements.

2.2. Characterization of the Physical–Chemical Properties of the Biofuel Mixtures

The kinematic viscosity was determined in all cases according to the criteria established in the European standard EN 590:2022, following the methodology described elsewhere [58–63]. The reported viscosity values are obtained as the average of three determinations, with a variation of less than 0.30% between measurements, as required by the American Society for Testing and Materials (ASTM) D2270-79 standard [85], method for calculating viscosity index.

The corresponding density values were obtained at 15 °C following the EN ISO 3675 [86] test method, whereas the cold flow properties, Cloud Point (CP) and Pour Point (PP), were determined following the EN 23015/ASTM D2500 [87,88] for Cloud Point, and the ISO 3016/ASTM D97 [89,90] for Pour Point [58–63]. All values were derived from the media value of duplicate determinations.

The calorific value (CV), or combustion heat, in kJ/kg, was obtained by a theoretical calculation following Equation (1). This property is a measure of the energy content of the fuel, related to the power output of the engine, which provides a fuel consumption estimate. Thus, the greater the calorific value, the lower the fuel consumption [71].

$$CV = \Sigma_i \, CV_i X_i \tag{1}$$

where CV_i is the calorific value of each component and X_i is the volumetric fraction of every component [72].

The cetane number (CN) parameter, according to norm EN 590:2022, must be above 51, to obtain the best ignition quality of a fuel in a diesel engine [73]. Cetane number values of the studied blends were obtained by Equation (2):

$$CN = \Sigma_i \, CN_i X_i \tag{2}$$

where CN_i is the cetane number of each component and X_i is the volumetric fraction of every component [55,72].

2.3. Performance and Exhaust Emissions of a Diesel Engine Fueled with the PO/SVO Double Blends and Diesel/PO/SVOs Triple Blends

The performance and exhaust emissions were analyzed in a diesel engine–electric generator set, following the same experimental methodology reported elsewhere and depicted in Figure 1 [58–63]. Engine specifications are shown in Table S1.
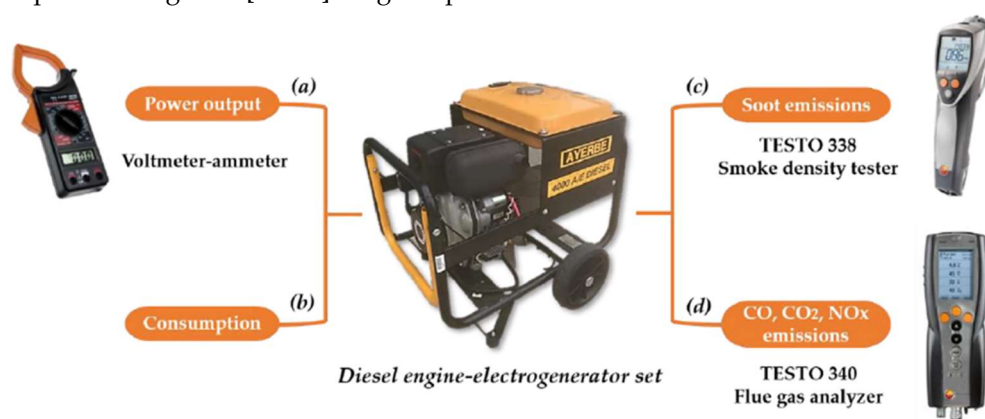

Figure 1. Experimental methodology for the biofuels evaluation using a diesel engine set based on (**a**) power output from a voltmeter–ammeter devise, (**b**) fuel consumption, (**c**) soot emissions using a smoke density tester, and (**d**) CO, CO_2, and NO_x emissions using a flue gas analyzer [63].

In every test, 0.5 L of biofuel was used with a 20 min runtime to reach stable operating conditions. The electrical power (P), in watts, was obtained with a voltmeter–ammeter using Equation (3):

$$P = V \cdot I \tag{3}$$

where V is the potential difference or voltage (in volts) and I is the electric current in-tensity or amperage (in amps).

The amount of consumed fuel was obtained from the time needed to spend an amount of fuel (0.5 L). Brake-specific energy consumption (BSFC) values, expressed in g/h·kW, were obtained with a biofuel volume of 0.5 L at three different engine loads: 1, 3 and 5 kW, representing low-, medium-, and high-power demands. BSFC results were obtained as the average of three measurements.

The contamination degree was based on the opacity of the smoke, as well the carbon monoxide (CO), nitrogen oxide (NO_x), and carbon dioxide (CO_2) generated by the engine in the combustion process. Opacity was obtained with an opacimeter-type TESTO 338 smoke density tester, following the standard method ASTM D-2156 [91] (Standard Test Method for Smoke Density in Flue Gases from Burning Distillate Fuels) (Figure 1c). The smoke emissions are expressed as a Bosch number, which is a standardized measurement unit with a range from 0 to 2.5. The absolute clarity of the soot measure paper is 0, and 2.5 is 100% paper blackening. However, levels of CO, NO_x, and CO_2 in the combustion exhaust gas were monitored using a Testo 340 flue gas analyzer (Figure 1d). The concentrations of CO and NO_x are reported in parts per million (ppm), while CO_2 levels are expressed as a volumetric percentage. Prior to each test, the analyzers were calibrated with zero gas. Table S2 displays the accuracy of the measurements used for the various parameters. These data represent the average of three repeated measurements, with an experimental error of less than 6%.

3. Results and Discussion

3.1. Physicochemical Properties of PO/SVO Double Blends, and D/PO/SVO Triple Blends

According to the results shown in Table 1, which show the physicochemical properties of diesel oil, sunflower oil, castor oil, and plastic oil, it is confirmed that kinematic viscosity is the most characteristic parameter that must be modified to replace fossil diesel with any of the two vegetable oils that were investigated, since both SVOs present much higher values for this parameter compared to fossil diesel. Thus, it is necessary to severely reduce their viscosities to obtain the approximate values required by European standard EN 590:2022, in the range 2.0–4.5 cSt. In this sense, the kinematic viscosity values of the different double mixtures of the two vegetable oils, investigated with the PO as the LVLC solvent, were calculated to find the percentages of the mixtures whose viscosities are closest to those of fossil diesel. The viscosity values of the PO/SVO double blends are shown in Table 2.

Table 2. Kinematic viscosity values in centistokes (cSt), at 40 °C, of plastic oil (PO)/sunflower oil (SO), and PO/castor oil (CO) double blends, with different proportions of plastic oil.

Plastic Oil (% by Volume)	PO/SO (cSt, Centistokes)	PO/CO (cSt, Centistokes)
0	37.8 ± 0.46	226.2 ± 0.55
10	28.12 ± 0.05	150.61 ± 0.54
30	14.15 ± 0.05	62.24 ± 0.09
60	6.74 ± 0.04	8.79 ± 0.25
80	4.29 ± 0.01	5.94 ± 0.05
90	3.12 ± 0.02	4.20 ± 0.03
100	2.47 ± 0.01	2.47 ± 0.01

By increasing the proportion of PO as an LVLC in blends, a significant decrease in viscosity was obtained in both SVOs, with this being much greater in the mix with CO according to the values of the mixtures presented in Table 2, which shows the most

suitable mixture to obtain an appropriate viscosity for these blends. Thus, using the range established by the European Standard EN 590:2022, suitable viscosity values for use in current diesel engines were achieved by incorporating 80% plastic oil in the case of sunflower oil (obtaining a viscosity of 4.29 cSt), and 90% in the case of castor oil, where a viscosity of 4.20 cSt was obtained.

Theoretically, these mixtures could be used in their pure form as biofuels in any conventional diesel engine, as well as in triple mixtures with the current fossil diesel. However, considering the previsible small changes that occur in the rheological properties of these mixtures, it is advisable to evaluate a series of triple mixtures to determine which mixture would have the best performance and the lowest amount of polluting emissions.

In this respect, the selected double mixtures (80% PO with SO and 90% PO with CO) will be used in the preparation of triple blends with fossil diesel, in various proportions, expressed as the following volume percentages: B10, B30, B60, B80, B90, and B100. Thus, the percentage of biofuel (PO/SVO mixture) added to the fossil diesel is expressed as B, where B0 corresponds to 100% of the fossil diesel and B100 corresponds to 100% of the double renewable PO/SVO mixture. The most relevant fuel properties of the blends obtained here are collected in Tables 3 and 4.

Table 3. Fuel properties of diesel (B0), PO/SO double blend (B100), and diesel (D)/PO/SO triple blends (B20SO–B80SO), containing 80% PO.

Fuel Blend	D/PO/SO	Kinematic Viscosity (cSt)	Density (kg/m^3)	Cloud Point (°C)	Pour Point (°C)
B0	100/0/0	3.20 ± 0.03	820.84 ± 0.02	−6.0 ± 1.0	−16.0 ± 1.2
B20SO	80/16/4	3.23 ± 0.03	829.85 ± 0.02	−4.8 ± 1.5	−8.1 ± 0.7
B40SO	60/32/8	3.40 ± 0.01	840.82 ± 0.03	−4.4 ± 0.7	−8.8 ± 1.2
B60SO	40/48/12	3.70 ± 0.04	898.95 ± 0.06	−3.9 ± 0.9	−6.4 ± 1.0
B80SO	20/64/16	4.03 ± 0.01	926.87 ± 0.03	−3.3 ± 1.0	−8.6 ± 0.3
B100SO	0/80/20	4.29 ± 0.01	951.67 ± 0.03	−1.8 ± 0.8	−9.5 ± 0.9

Table 4. Fuel properties of diesel (B0), PO/CO double blend (B100), and D/PO/CO triple blends (B20CO–B80CO), containing 90% PO.

Fuel Blend	D/PO/CO	Kinematic Viscosity (cSt)	Density (kg/m^3)	Cloud Point (°C)	Pour Point (°C)
B0	100/0/0	3.20 ± 0.03	820.84 ± 0.02	−6.0 ± 1.0	−16.0 ± 1.0
B20CO	80/18/2	3.21 ± 0.04	831.67 ± 0.02	−4.1 ± 1.5	−9.5 ± 1.2
B40CO	60/36/4	3.23 ± 0.03	842.55 ± 0.04	−3.4 ± 0.9	−9.8 ± 1.4
B60CO	40/54/6	3.45 ± 0.03	853.83 ± 0.03	−4.8 ± 1.4	−8.3 ± 0.9
B80CO	20/72/8	3.72 ± 0.03	860.00 ± 0.01	−6.2 ± 0.9	−8.9 ± 1.0
B100CO	0/90/10	4.20 ± 0.03	881.67 ± 0.04	−3.6 ± 1.1	−8.5 ± 1.4

The obtained results show that an increase in biofuels (PO and SVO) in the triple mixtures produces a slight increase in the density. Regarding the cold flow properties, a slight increase was obtained in Cloud Point values, as well a higher increase in Pour Point values, with both studied vegetable oils. These values allow for the use of these mixtures in cold climates, although they are less suitable than conventional fossil diesel. This behavior is very similar to that obtained using other organic solvents as LVLC additives in double and triple mixtures with the same pure castor and sunflower vegetable oils [58–63].

3.2. Mechanical Performance of a Diesel Engine, Working as Electric Generator, Fed with Different Biofuel Blends

The mechanical and environmental efficiency of the double mixtures B80SO and B90CO, as well as all triple diesel/PO/SVO mixtures collected in Tables 3 and 4, are also evaluated when operating as a biofuel in an electric generator powered by a conventional

diesel engine to determine the optimal mixtures for each investigated SVO. Figure 2 illustrates the power output across various engine loads (0–5 kW) for triple blends incorporating sunflower oil (Figure 2a) or castor oil (Figure 2b), alongside diesel as a reference. Additionally, it includes the pure biofuels composed of the double mixtures B100SO and B100CO for comparison.
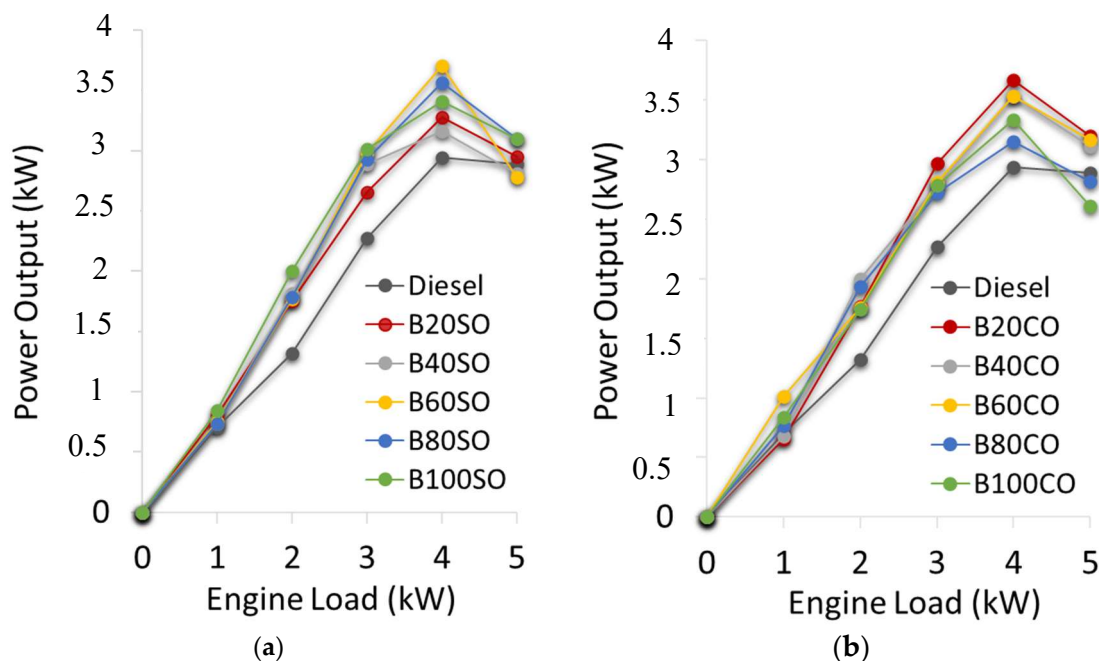

Figure 2. Power output (kW) variation obtained by operating at different engine loads, using different power demands, with the different triple mixtures (**a**) D/PO/SO and (**b**) D/PO/CO. The experimental error was always less than 8% when repeating the corresponding measurements.

According to the results, generated power increases upon increases in the power demanded from 1 kW to 4 kW, with a stabilization at 4.0 kW of the generated power, followed by a slight decrease at 5 kW, the maximum power that was demanded. This behavior is close to that found in previous studies, which used other LVLC solvents with the same AO and SO vegetable oils [58–63]. However, unlike the previously described results with other LVLC solvents, in this case, the presence of biofuels improves the behavior of fossil diesel in all cases with both studied oils, and in any proportion in triple blends. This behavior can be attributed to the higher energy content of the studied mixtures compared to commercial diesel, because of the incorporation of the PO/SVO mixtures, with a higher calorific value, due to the high calorific value and cetane number of plastic oils, as shown in Table 1.

The only difference detected between both of the studied vegetable oils in terms of the power generated refers to the proportions of the most efficient triple mixtures. In the case of sunflower oil, maximum efficiency is obtained with B60SO, while, with castor oil, the maximum efficiency was achieved with the B20CO mixture. In both cases, these triple mixtures present a greater efficiency than either of the two double mixtures, B100SO or B100CO. It therefore appears that the presence of a certain amount of fossil diesel in the form of a triple mixture improves the performance of pure diesel or any of the double mixtures. However, all the mixtures studied in Tables 3 and 4, including PO/SVO double blends without any fossil diesel, can be used as biofuels with a greater efficiency than pure fossil diesel, achieving a 100% substitution of fossil fuel.

3.3. Brake-Specific Fuel Consumption (BSFC)

The greater power generated with the different triple and double mixtures should lead to a lower biofuel consumption, which can be obtained from the product of brake-specific

fuel consumption (BSFC) and calorific value. This is a crucial parameter for any biofuel aiming to substitute fossil diesel in the existing vehicle fleet. Lower BSFC values at any power output indicate higher engine efficiency. Figure 3 illustrates the variation in BSFC at low (1 kW), medium (3 kW), and high (5 kW) engine loads, showcasing different PO/SO and D/PO/SO blends (Figure 3a), as well as PO/CO and D/PO/CO blends (Figure 3b).
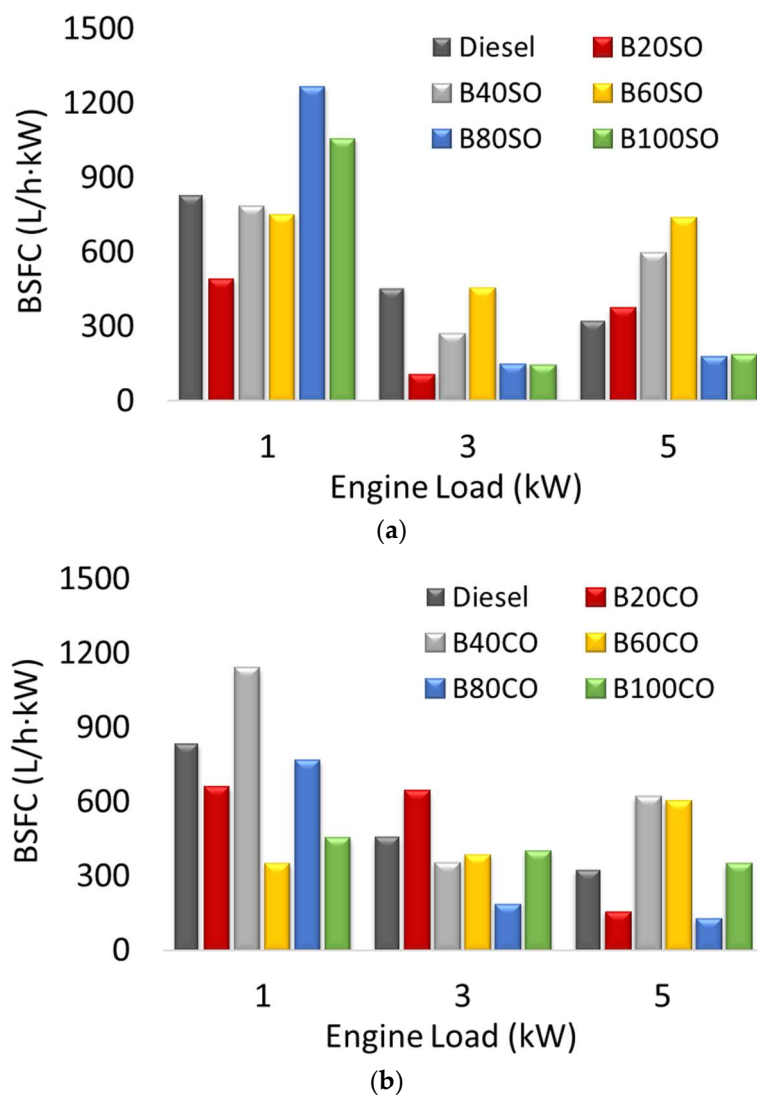

(**a**)

(**b**)

Figure 3. Influence of both (**a**) PO/SO and (**b**) PO/CO biofuels at low, medium, and high engine loads (1, 3, 5 kW) on BSFC (g/h.kW) values.

According to the results, in all biofuel mixtures, the BSFC values generally decrease with increases in engine load. Thus, the highest BSFC values are obtained with the lowest loads, decreasing when average load values are used, and remaining practically constant at the highest load values. This behavior seems to be due to the increase in temperature inside the cylinder as the engine load increases, which enhances the combustion process, leading to a drop in the BSFC values [92]. It can also be observed in Figure 3a,b, that, on increasing the PO amount in the blends, as shown in Tables 2 and 3, there is a decrease in BSFC values in this mixtures, whether composed of SO or CO, corresponding to the increase in their calorific values, which increases the energy content of the blends. Consequently, diesel exhibits the lowest calorific value (Table 1), and generally has the highest BSFC value. When operating at medium and high powers, 3 kW and 5 kW, respectively, are obtained as the intermediate values of biofuels B60SO or B20CO, higher BSFC values with respect to pure diesel as well as the corresponding double mixtures, B100SO or B100CO. However,

the triple mixtures, B80SO and B80CO, show the lowest BSFC values, and therefore are more suitable as they will allow the engine to operate with the minimum fuel consumption.

3.4. Exhaust Emissions from Diesel Engine

3.4.1. Soot Emissions

The values regarding the opacity of smoke emissions obtained for different engine loads with the different biofuel blends containing SO (Figure 4a) or CO (Figure 4b) are plotted in Figure 4. There is a noticeable increase in smoke emissions when mixtures contain castor oil, as compared with the mixtures using sunflower oil in the same proportion. The greatest production of soot emissions occurs when mixtures containing castor oil are employed, which can be ascribed to the greater amount of unsaturation in linoleic acid in sunflower oil compared to ricinoleic acid in castor oil, since the decomposition of unsaturated compounds gives rise to polycyclic aromatic hydrocarbons (PAHs), which are subsequently transformed into soot particles [93].
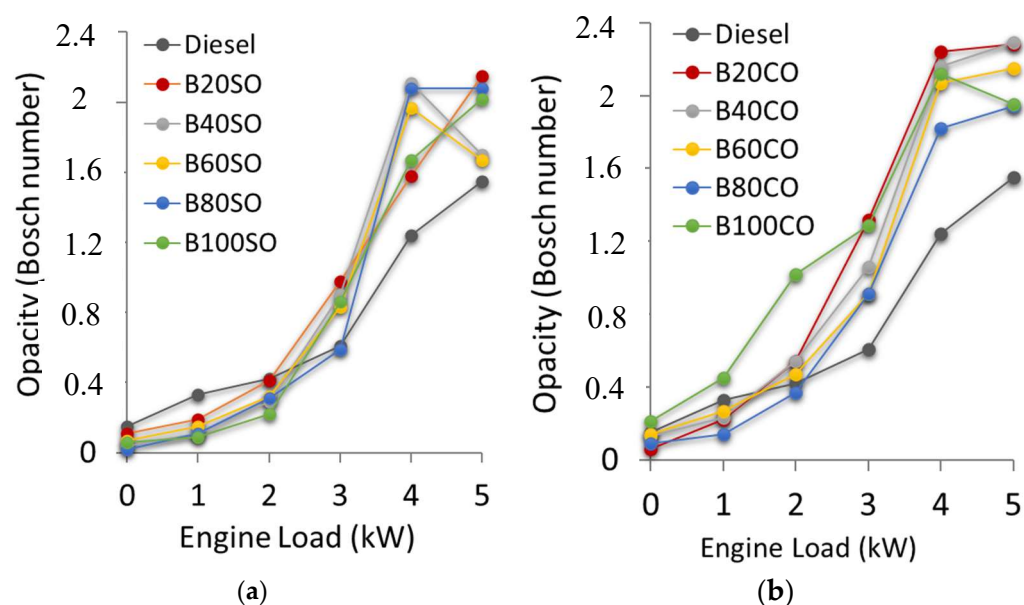

Figure 4. Opacity of soot emissions (measured in Bosch number) produced at various engine operating powers (ranging from 0 to 5 kW), depending on the triple blends: (**a**) diesel/PO/sunflower oil and (**b**) diesel/PO/castor oil.

The obtained opacity values are higher than those exhibited by the triple blends in which other LVLCs were employed, such as the mixture of acetone/butanol/ethanol [63] or dimethyl carbonate [61]. However, the significant point here is that waste generated in the industry, such as plastic oil, is being valorized, which could make the process appealing at an industrial scale. Furthermore, it should be noted that the values comply with legislation, so this blend could be used in the current vehicle fleet from this point onward.

3.4.2. Carbon Monoxide (CO) Emissions

The CO amounts, in parts per million (ppm), detected in the smoke emissions generated at the different engine operating powers, with the different double and triple mixtures, are shown in Figure 5a (D/PO/SO) and Figure 5b (D/PO/CO).
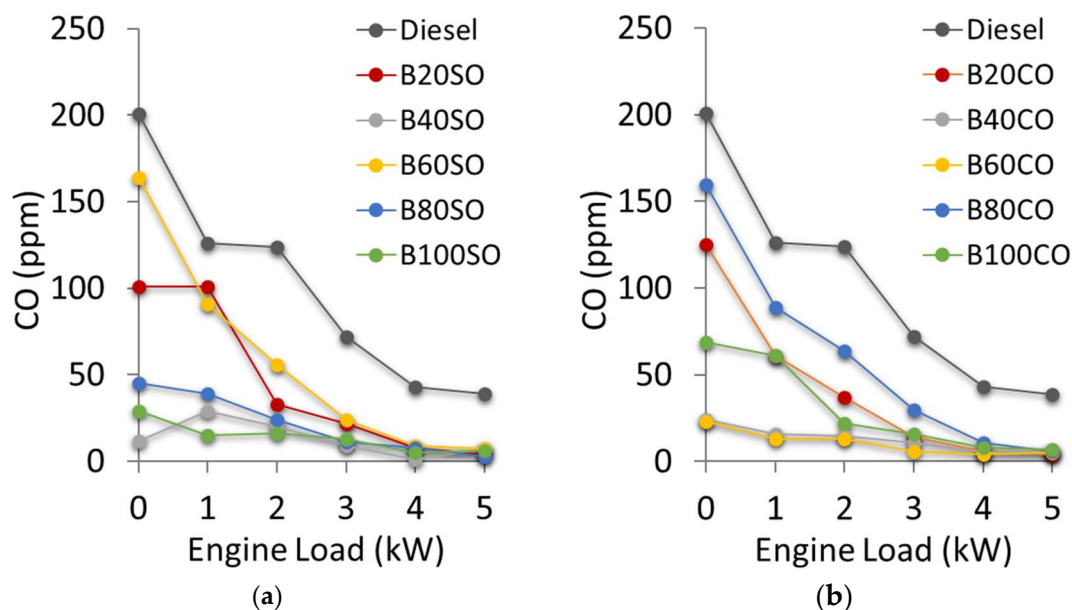
Figure 5. Carbon monoxide (CO) emissions (in ppm) produced at various engine operating powers (ranging from 0 to 5 kW). Values obtained with (**a**) diesel/PO/sunflower oil and (**b**) diesel/PO/castor oil.

Generally, according to the results, the CO emitted by all the triple blends was lower than that emitted by diesel, and lowered as the percentage of biofuel in the blend increased. These results indicate that fossil diesel has a higher level of CO emissions than either of the two PO/SVO double mixtures. In fact, these two double mixtures, PO/SO and PO/CO, present the minimum emission levels, except for the triple mixtures B40CO and B60CO. Furthermore, a decrease in the concentration of CO is observed upon increases in the working power of the engine in all cases.

3.4.3. Carbon Dioxide (CO_2) Emissions

The corresponding CO_2 values, measured as a percentage, are detected in the emissions generated when operating at the different engine operating powers, and the different mixtures are shown in Figure 6a (D/PO/SO) and Figure 6b (D/PO/CO). The results obtained with both oils show that CO_2 emissions increase as the power demanded by the engine and the concentration of biofuels in the triple blends increase. Samples in which castor oil participates always had higher CO_2 emissions than those produced by fossil diesel, although these differences mainly occurred at high engine loads (3, 4, and 5 kW). In fact, almost double the percentage (4% of CO_2) was obtained compared to B20CO and B40CO. However, samples with a greater presence of biofuel (B80CO and B100CO) exhibited a behavior more akin to that of fossil diesel. Blends composed by sunflower oil performed differently. In fact, a very similar behavior to fossil diesel was obtained, with the highest CO_2 emission value of 3% being achieved with the B60SO sample. It must be highlighted that, even with B20SO and B40SO, lower CO_2 emission values were obtained than with diesel at 5 kW.
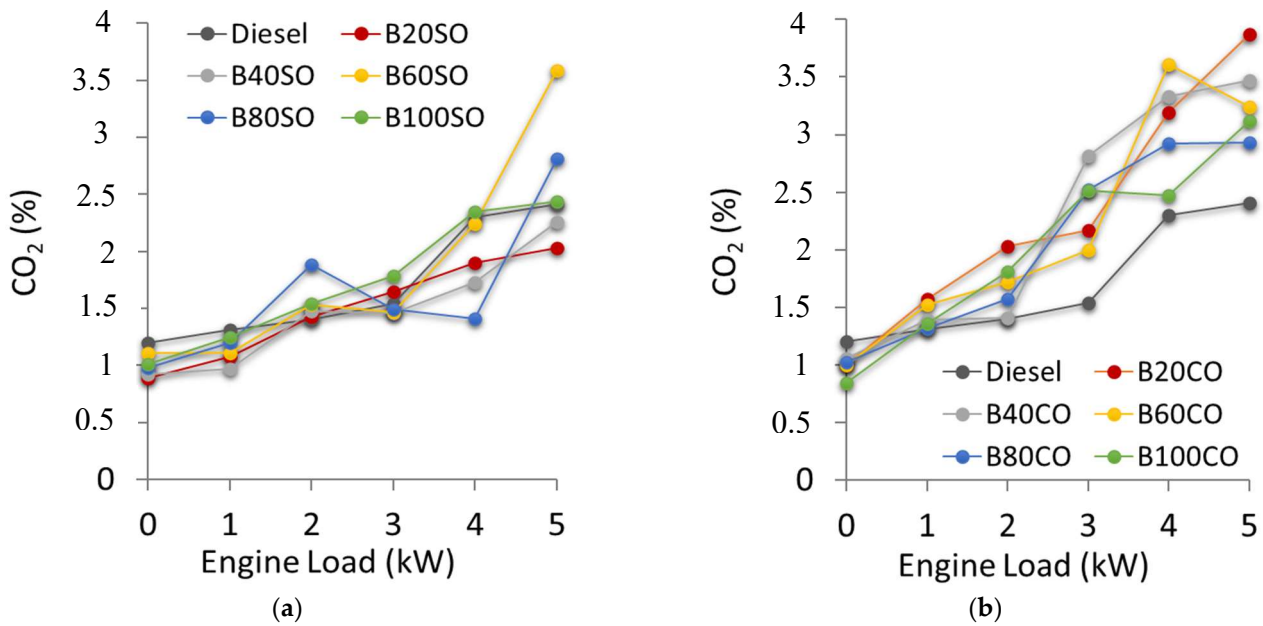
(a) (b)

Figure 6. Carbon dioxide (CO_2) emissions as the gas's percentage, obtained with various engine operating powers (ranging from 0 to 5 kW). Values obtained with (**a**) diesel/PO/sunflower oil and (**b**) diesel/PO/castor oil.

3.4.4. Nitrogen Oxides (NO_x) Emissions

The NO_x amounts, in parts per million (ppm), detected in the generated emissions are depicted in Figure 7a (D/PO/SO) and Figure 7b (D/PO/CO).
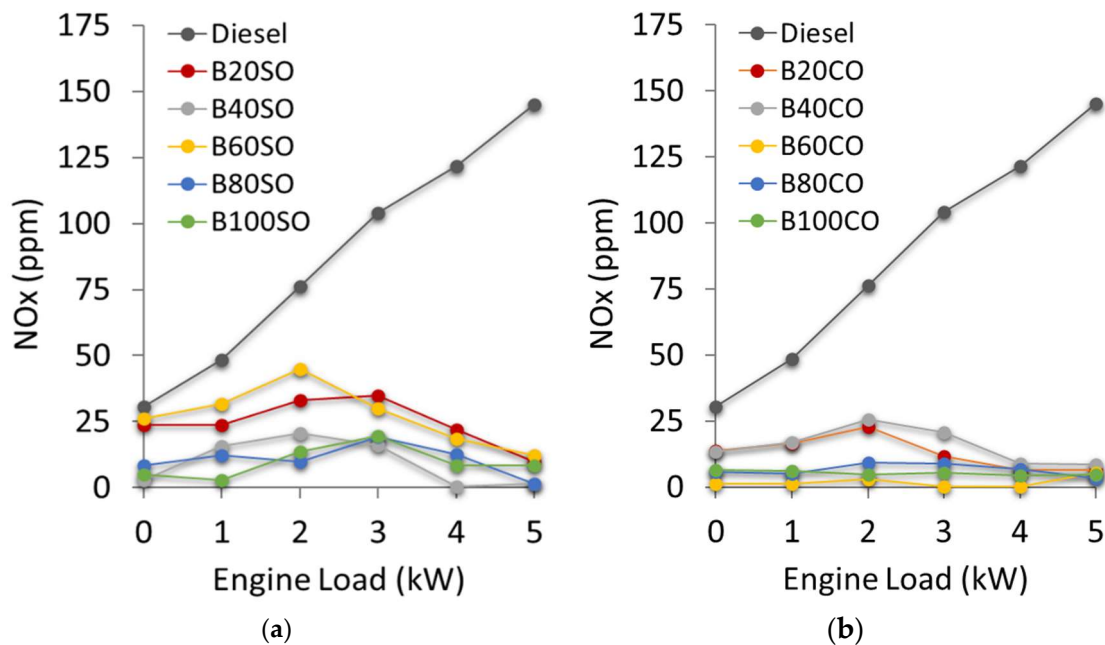

(a) (b)

Figure 7. Nitrogen oxide (NO_x) emissions (in ppm) obtained with various engine operating powers (ranging from 0 to 5 kW). Values obtained with (**a**) diesel/plastic oil/sunflower oil and (**b**) diesel/plastic oil/castor oil.

The obtained results show that, at higher engine powers, the values of NO_x emissions produced during the combustion of fossil diesel linearly increase, while the values of the emissions obtained with all the mixtures are always much lower. On the other hand, in the mixtures containing sunflower oil (Figure 6a), generally, the values of the produced

NO_x emissions are higher than those of the mixtures containing castor oil (Figure 6b), with a maximum being obtained at the intermediate values of engine power in both mixtures. Furthermore, the higher the concentration of biofuel, the lower the emission values. In fact, the lowest emission values at all the studied engine powers were obtained with the B100SO and B100CO samples.

4. Conclusions

In this research, plastic oil, a waste obtained from the pyrolysis of plastics, was employed for the first time, to the best of our knowledge, as a low-viscous low-cetane (LVLC) number compound mixed with straight vegetable oils (SVOs) and fossil diesel. The behavior of these blends was evaluated in an internal combustion engine.

Thus, several triple blends obtained from a convenient double blend of either plastic oil/sunflower oil or plastic oil/castor oil and diesel were studied. The results show that, in certain proportions, these triple mixtures D/PO/SVO exhibited a behavior that make them susceptible to being used in the engines of the current fleet of vehicles, since similar or even higher power output values (kW) than fossil diesel was obtained, without excessive fuel consumption and with emissions that fulfil the current legislation. In fact, these emissions are in most cases lower than those obtained with fossil diesel.

Therefore, triple blends such as B60SO, B80SO, B60CO, and B20CO could constitute good alternatives to substitute fossil diesel. The only inconvenience might be their behavior in cold climates, particularly those blends in which sunflower oil is present.

Abbreviations

ASTM	American Society for Testing and Materials
B0	100% diesel
B20CO	80% diesel + 20% plastic oil/castor oil blend
B40CO	60% diesel + 40% plastic oil/castor oil blend
B60CO	40% diesel + 60% plastic oil/castor oil blend
B80CO	20% diesel + 80% plastic oil/castor oil blend
B100CO	100% plastic oil/castor oil blend
B20SO	80% diesel + 20% plastic oil/sunflower oil blend
B40SO	60% diesel + 40% plastic oil/sunflower oil blend
B60SO	40% diesel + 60% plastic oil/sunflower oil blend
B80SO	20% diesel + 80% plastic oil/sunflower oil blend
B100SO	100% plastic oil/sunflower oil blend
BSFC	Brake-specific fuel consumption

C.I.	Compression ignition
CN	Cetane number
CO	Castor oil
CP	Cloud point
cSt	Centistokes
CV	Calorific value
D	Diesel
ISO	International Standards Organization
LVS	Low-viscosity solvent
PP	Pour point.
Rpm	Revolutions per minute
SO	Sunflower oil
SVO	Straight vegetable oil
VO	Vegetable oil
W	Watts
Symbols	
C	Calibration constant $(mm_2/s)/s$
T	Flow time (s)
υ	Viscosity (centistokes)

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