

The Properties of Diesel Blends with Tire Pyrolysis Oil and Their Wear-Related Parameters

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Abstract: This research presents the impact of diesel blends with tire pyrolysis oil (TPO) as an additive for minimizing the wear and tear of engine components. This study investigates the blends of normative diesel oil with TPO content ranging from 5% m/m to 20% m/m. Reference measurements are made for pure diesel oil (D100) and pure TPO. This investigation included an evaluation of the corrosion effect and the effect of the fuels tested on abrasive wear. For each fuel, the sulfur content, water content, lubricity (which is defined as the corrected average diameter of the wear trace during the high-frequency reciprocating rig (HFRR) test), and impurity content are determined. Impurities are assessed using indicators such as ash residue, coking residue from 10% distillation residue, determination of wear metals and contaminants, insoluble impurity content, and total sediment by hot filtration. All parameters are determined using recognized methods described in international standards. Approximation models are built for all the analyzed parameters, which can be used in future studies. At the same time, the individual values of the analyzed factors are compared with the threshold values specified in selected standards and regulations. Consequently, it is possible to assess the usefulness of individual fuels in terms of meeting the requirements for minimum wear of engine components. The results show the suitability of pyrolysis oil and the potential for its use as an additive to fossil fuels in terms of meeting most factors. Some of the fuels tested did not meet the standards for acceptable sulfur content. However, in terms of sulfur content, all of the analyzed fuels can be used to power watercraft and land-based power and thermal power plants equipped with flue gas desulfurization systems. A second indicator for not meeting the standards is the ash residue value, which indicates the high content of non-combustible, mainly metallic, substances in the pyrolysis oil used for the tests. Post-recycled oils must, therefore, undergo appropriate purification before being used as an additive to diesel fuels for internal combustion engines. Once the post-recycling oil has been subjected to desulfurization and advanced filtration, it can be used as a fuel additive for land

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vehicles, which fits in with closed-loop economies and sustainable development strategies.

Keywords: diesel oil and pyrolytic oil fuel blends; tire fuel; lubricity; sulfur; contamination; ash; carbon residue; total sediment; engine wear; corrosion

1. Introduction

Modern energy and transportation sectors face a major challenge in reducing emissions and seeking sustainable solutions for delivering energy. Maritime and land transportation are dominated by means of transportation powered by internal combustion engines. One solution to reduce the use of fossil fuels is the use of alternative fuels, including those supplemented with bio-based and recycled waste additives. One of the additives that have the potential for wider use are oils known as tire recycled fuels or pyrolysis oils (TPO) [1]. The use of such diesel oil additives offers an opportunity to utilize hard-to-recycle wastes, reduce operating costs, and reduce consumption of natural resources. Worn car tires pose a threat to road users due to the deterioration of the tire's interaction with the road surface and the increasing risk of mechanical damage to the tire. Worn tires also pose a significant burden on the environment due to particulate emissions resulting from the tire abrasion process that occurs during the use of the vehicle on which the tires are mounted [2].

Approximately 1.5 billion used tires are generated annually, with around 5 million tons found in Europe, Japan, and the United States [3]. Tires are resistant to biological and thermal degradation due to the vulcanization process, which involves treating a mixture of natural and synthetic rubber. After vulcanization, tires acquire a three-dimensional, cross-linked chemical structure, significantly hindering their biodegradation and photochemical decomposition under natural conditions. Consequently, most developed countries have restricted the disposal of tires in landfills [4–6].

The composition of tires remains largely consistent, allowing for classification based on the following mass proportions: natural rubber (20–25%), styrene-butadiene rubber (30–50%), butyl rubber (up to 30%), carbon black (approximately 30%), sulfur (1–2.5%), and small amounts of organic and inorganic additives, depending on the manufacturer and the intended use of the tire [7–9].

Currently, the primary methods for processing used tires include direct reuse, land-filling, incineration, refurbishment of old tires, rubber recovery, and pyrolysis [10–12]. Over the past decade, the pyrolysis of used tires has gained popularity due to its efficient and environmentally friendly recovery of energy and organic compounds from waste. In the “waste-to-energy” sector, the pyrolysis of solid waste has been extensively studied. Various feedstocks, such as wood, agricultural waste, and more recently, microalgae, have been converted into high-yield bio-oil through the pyrolysis process [13,14].

Pyrolysis can fully process large amounts of rubber waste while producing high-value products such as pyrolytic oil, carbon black, and high-calorific-value fuel gas. This method is considered promising from both the environmental and the economic perspectives [15]. For used tires, the pyrolysis process involves heating the material to a specific temperature, initiating the breakdown of long molecular chains into shorter ones, ultimately yielding three main products: pyrolytic oil, pyrolytic gas, and pyrolytic carbon black [16]. The process results in a high yield of oil that can be used as fuel, as well as a high-calorific gas that can serve as a fuel source during the process, and residual carbon that can be used as smokeless fuel, carbon black, or activated carbon [12].

Such oil can be used as an additive to diesel fuel. However, to be utilized in this form, it must comply with the regulatory requirements governing fuel standards. Diesel fuel standards for both land and maritime applications are strictly regulated by various legal acts. On land, the fuel must meet the quality standards set forth in Directive 2009/30/EC, which specifies the maximum sulfur content and other parameters, as well as in EN 590, which details the quality requirements for diesel fuel used in land vehicles [13,17]. In the United States, EPA regulations also impose sulfur content limits, defining standards for Ultra-Low Sulfur Diesel (ULSD) [18]. In maritime applications, regulations derived from the MARPOL Convention, particularly Annex VI, and Directive 2012/33/EU establish stringent sulfur content limits for fuels used by ships, aiming to protect the marine environment [19,20]. Additionally, the International Maritime Organization (IMO) globally regulates the quality of marine fuels, including diesel requirements for marine engines [21].

Used tires must, therefore, be disposed of. The effective life of tires is about four years [22]. At the end of this period, tires become waste, most of which ends up in landfills. One way to manage them is to recover energy by burning them in the furnaces of thermal power plants or cement plants, which is a significant burden on the environment [23]. Another way to use waste tires is to produce liquid fuels [24] and gaseous fuels [25], which can be used as pure fuels or components added to conventional fuels. Therefore, research is needed to evaluate the physical and chemical properties of tire-derived fuels compared with conventional fuels.

The introduction of recycled fuel into the fuel carries with it the need to evaluate the impact of such fuel blends on the operation of the internal combustion engine, including the wear processes of contacting components in the fuel and engine system [26].

The effect of fuel and its combustion products on the wear of engine components and associated equipment (i.e., fuel supply system, lubricating oil system, and exhaust gas system) can be evaluated using several indicators describing fuel properties [27]. Selected indicators and their relationship to the degradation processes of engine components are shown in Table 1.

Table 1. Indicators characterizing the effect of fuel on the degradation processes of internal combustion engine components (own elaboration based on refs. [27,28]).

Indicator	Designation	Unit of Measurement	Associated Processes Characterized Directly or Indirectly Before the Indicator	Degradation Processes of Engine Components					
				Sludge and carbon formation	Low-Temperature corrosion	High-Temperature corrosion	Abrasive Wear	Erosion Wear	Contamination and biological corrosion
Sulfur content of fuel	C_s	% m/m	Formation of toxic sulfur oxides, sulfuric acids, and sulfate	++	++	+	+/+ *	+	
Water content of fuel	C_w	% m/m	Formation of corrosion compounds, creation of an environment for corrosion processes, deterioration of friction conditions, and creation of an environment for the growth of microorganisms	+	++		++	++	
Fuel lubricity	$WS_{1.4}$	μm	Fuel's ability to form a boundary layer at tribological nodes	+			++		
Coke residue (from 10%	X_{CR}	% m/m	Content of heavy hydrocarbons in fuel	++			+		

distillation residue)							
Ash residue	X_A	% m/m	Content of solid mineral particles and metallic soaps in fuel	+	++	++	+
Total sediment by hot filtration (% m/m)	X_s	% m/m	Content of mechanical impurities contained in fuel	+	+	++	++
Content of insoluble impurities	X_c	mg/kg	Content of mechanical impurities contained in fuel	+		++	++

* An indicator can have both positive and negative effects on the engine component degradation process.

A double plus sign (++) in Table 1 marks the direct association of an indicator with the intensification of a specific engine component degradation process. A single plus sign (+) marks the indirect association of an indicator with the intensification of a specific engine component degradation process (several degradation factors are required to occur simultaneously for the process to occur).

Among such indicators describing the effect of fuels on the degradation processes of the engine and associated equipment are the sulfur content of the fuel [29], the water content of the fuel [30], the lubricity of the fuel [31], the residue after coking [32], the residue after incineration [33], total sediment by hot filtration [34], the content of insoluble impurities [35,36], and the content of elements associated with wear processes [37]. The method of determining the value of each of these indicators has been standardized and is described in detail in a number of international standards. It should be noted that due to the multiplicity of standards and equipment for carrying out measurements, it is necessary to indicate how a given measurement was carried out so that it is possible to compare the results obtained by different researchers.

The limit values of these indicators are given in normative documents. Minimum requirements for the quality of marine fuels are described in [38], which includes specifications of marine fuels. Additional environmental requirements are indicated in Annex VI of the International Convention for the Prevention of Pollution from Ships MARPOL [39]. Meanwhile, EU regulations and the resulting national regulations apply to fuels used on land, such as the Regulation of the Minister of Economy of Poland RMG [40].

The water and sulfur content indirectly indicates the corrosive properties of the fuel, as the combustion of sulfur produces environmentally harmful sulfur oxides (SO_x), which in turn are anhydrides of highly corrosive sulfuric acids [41]. These acids cause low-temperature corrosion with the abrasion of piston rings and cylinder liners [42]. In addition, chemical reactions of sulfuric acid with sodium from fuel or lubricating oil produce Na_2SO_4 , which causes high-temperature corrosion of exhaust valves. At the same time, a substance with good lubricating properties, i.e., sulfur, reduces the abrasive wear of contacting components by reducing the coefficient of friction [43], which can have a beneficial effect on reducing the abrasive wear of precision injection pump pairs and injectors [44] and pistons, piston rings, and cylinder liners [45]. However, sulfur in the combustion chamber also causes adhesion of a black varnish-like layer on the slide faces of the cylinder liners [41]. In turn, water present in the fuel can contribute to the fouling of these components [46]. Water and sulfur also contribute to the growth of contaminating and corrosive bacteria.

Lubricity is the behavior of a lubricant when elements of a tribological pair cooperate under boundary friction conditions. It is not a fundamental physical parameter but a complex characteristic [47] that, in addition to the parameters of the oil, also depends on other factors such as contact geometry, structural materials, and the characteristic of movement

of the contacting elements and loading conditions [48]. There are many measures describing lubricity due to the lack of a uniform definition for it [49]. One of the most common measures of lubricity indicated in normative documents is the corrected average wear scar size $WS_{1.4}$, relating to a reference pressure of 1.4 kPa [31]. The smaller the value of this parameter, the better the lubricity properties of a given fuel.

Parameters, such as coking residue from 10% distillation residue and total sediment by hot filtration [50], can be used to characterize the fuel, including its effect on the formation of carbon build-up and fouling of engine parts in contact with a given fuel or its products of combustion. These indicators also describe the effect of fuel on the abrasive wear of engine components in contact with the fuel or its combustion products [51]. In addition, the effect of fuel on abrasive wear processes and corrosive effects can be described using the parameter incineration residue (ash residue), which indicates the content of incombustible components, mainly metallic, contained in the fuel. Metals contained in ashes, which take part in chemical reactions as substrates or catalysts, intensify corrosion processes in the exhaust system [52] and affect the formation of harmful substances in the exhaust gas [53].

The results of earlier studies conducted at various centers [54] showed, among other things, a deterioration relative to pure diesel fuel of such parameters for fuels with the addition of tire pyrolysis oil as a cold filter plugging point temperature t_{CFPP} and flash point temperature t_{FP} . At the same time, a favorable effect of the addition of synthetic fuel on reducing the level of emissions of hydrocarbons (HC) and nitrogen oxides (NO_x) was reported [55]. With the development of new materials used in industry and engines [56,57], a thorough analysis of the potential impact of fuel additives used in engines, including alternative fuels such as biodiesel or pyrolysis oil from tires, is necessary. This requires additional research due to parallel ongoing studies in these areas. In order to obtain a more complete characterization of fuels containing tire pyrolysis oil additives, it is necessary to evaluate the effect of such additives on the wear processes of engine components and associated equipment.

With this in mind, the present authors undertook an experiment to study the effect of a fuel consisting of D100 diesel fuel with recycled fuel (TPO) additive obtained from tire pyrolysis on the change in fuel properties in the context of its effect on the wear of engine components through the direct effect and indirect effect of combustion products of such fuels. In this analysis, blends with different proportions of TPO ranging from 5% to 20% m/m are considered, as well as the properties of pure base oils. The obtained results relate to the normative limit values indicated in selected documents.

The aim of the undertaken research is to conduct as comprehensive an analysis as possible of pyrolytic oil as an additive to diesel fuel as well as present the results of research on the suitability of pyrolytic oil as an additive to diesel fuel, focusing on the parameters that represent the properties of the mixture in terms of their impact on engine component wear. Due to the need to investigate various properties of pyrolytic oil and its mixtures with diesel fuel, including ignition and combustion properties, impact on engine component wear, rheological properties, and effects on the composition of exhaust gases emitted by the engine, it was necessary to divide the entire issue into a series of separate tasks included in other works by the authors.

In this article, we present the results of research on the suitability of pyrolytic oil as an additive to diesel fuel, focusing on the parameters that represent the properties of the mixture in terms of their impact on engine component wear.

2. Materials and Methods

The study of the analyzed fuels with different recycled oil content in terms of their effect on the wear of engine components was realized by determining their sulfur content

and water content and determining parameters such as lubricity, coking residue from 10% distillation residue, ash residue, and total sediment by hot filtration. All the measurements were carried out using standardized methods, a summary of which, along with a presentation of the apparatuses used, is given in Table 2.

Table 2. Summary of the methods and apparatuses used in the experiment.

Parameter Group	Parameter	Designation	Unit of Measurement	Method Used	Apparatus Used
Indicators describing the composition of blends	Sulfur content	C_s	% m/m	EN ISO 8754:2003+Ap1:2014-02P [29]	SLFA-2800 X-ray fluorescence spectrometer (Horiba, Kyoto, Japan)
	Water content	C_w	% m/m	EN ISO 12937:2005+Ap1:2021-11P [30]	Metrohm coulometer 831 KF (from Metrohm, Herisau, Switzerland)
Indicators describing the effect of blends on the wear processes of engine components	Lubricity (HFRR wear scar diameter) @ 60 °C	$WS_{1.4}$	μm	EN ISO 12156-1:2023 [31]	High-Frequency Reciprocating Rig HFRR V1.0.3 (PCS Instruments, London, UK)
	Coke residue (from 10% distillation residue)	X_{CR}	% m/m	EN ISO 10370:2014-12 [32]	Automatic micro MCRT 160 coke residue determination apparatus (Alcor Inc., Smithfield, RI, USA)
	Ash residue	X_A	% m/m	EN ISO 6245:2008 [33]	FCF 2.5M muffle furnace (Czylok, Jastrzębie Zdrój, Poland)
	Contaminant content / total sediment by hot filtration	X_s	% m/m	ISO 10307-1:2009 [34]	Setaclean Total Sediment Tester Apparatus (Stanhope-Seta, Chertsey, UK)
Content of mechanical insoluble impurities		X_c	mg/kg	EN 12662:2024-11 [36]	Suction flask under vacuum and drying oven and a scale RADWAG WPs 510/C/2 (RADWAG Wagi Elektroniczne, Radom, Poland)

The measurements were made in a certified laboratory accredited by the Polish Accreditation Center, which is a national accreditation body authorized to accredit conformity assessment bodies under the Law of 13.04.2016. on conformity assessment and market surveillance systems (Dz.U. 2022 poz.1854). In accordance with procedures, each measurement was performed twice to confirm the conformity of the measurement with normative documents. The authors determined the measurement uncertainty values based on the calibration certificates of the measuring instruments used.

Oils with the characteristics shown in Table 3 were used to prepare the blends. In the experiment, the wear properties of fuels obtained as a mixture of diesel oil without FAME additives (D100 oil) with recycled fuel oil obtained from tire pyrolysis were evaluated.

Table 3. Characteristics of the base fuels used to prepare fuel blends.

Parameter	Unit	Measurement Standard	Diesel Oil (D100)	Recycled Oil (TPO)
Density @ 15 °C ρ_{15}	kg/m ³	EN ISO 12185:2002 [58]	836.4	931.9
Kinematic viscosity @ 40 °C ν_{40}	mm ² /s	EN ISO 3104:2021-03 [59]	2.728	5.096
Kinematic viscosity @ 100 °C ν_{100}	mm ² /s	EN ISO 3104:2021-03 [59]	1.173	1.620
Lower heat value W	MJ/kg	PN-C-04062:2018-05 [60]	45.46	42.16
Flash point temperature t_{FP}	°C	EN ISO 2719:2016- [61]	64	38
Elemental composition	Fe	ASTM D6595-17 [62]	0.0	0.0
	Cr		1.1	0.1
	Pb		7.3	10.2
	Cu		0.0	1.2
	Sn		7.4	10.0
	Al		2.5	0.6
	Ni		7.6	13.0
	Ag		0.5	0.1
	Si		27.0	1.4
	B		1.0	1.5
	Mg		0.0	0.1
	Ba		0.0	0.0
	P		0.0	0.0
Zn	9.5	1.2		
Mo	1.3	1.4		
Ti	1.7	0.9		
V	0.0	0.0		

The experiment used standard diesel fuel (D100) without FAME. This fuel meets the requirements of ISO 8217:2024 as an ISO-F-DMX category fuel and complies with EU guidelines as a base oil without bio-additives [38].

The pyrolysis oil was obtained from Tire Eco Fuel Sp. z o.o. in Szczecin, Poland. The raw material used for pyrolysis consisted of standard used car tires. The pyrolysis process was carried out in a batch rotary reactor. The reactor charge (40 m³) was heated to a temperature within the range of 500 to 550 °C using diaphragmatic burners that combusted gaseous products generated during pyrolysis. The charge remained at this temperature for between 20 and 30 h. Under these conditions, various reactions occurred within the raw material, including dehydration, dehydrogenation, isomerization, aromatization, and others.

The products of the process included a gas fraction (15–25%), a condensing fraction (35–55%), and char (pyrolytic carbon black containing metal carcass elements) (35–55%). The entire condensing fraction was collected and homogenized. The resulting pyrolysis oil is a broad hydrocarbon fraction with a boiling point range of 35 to 500 °C. The physicochemical parameters of the oil used were summarized in our previous work published [63]. The properties of the oil are consistent with those described in the literature [64,65].

In this study, the blends were diesel fuel D100 with TPO at known mass percentages of the TPO in the blend equal to 5% m/m, 7% m/m, 10% m/m, 15% m/m, and 20% m/m. The liquid was homogenized. The type B standard uncertainty of the mass concentration estimate for all samples tested was 0.0023% m/m. For the mass shares of recycled oil in the blend, measurements were made of all the indicators.

Mathematical models approximating each parameter as a function of the mass share of pyrolysis oil in the tested fuel were built for each of the measurement results. These models can be used in further studies of these fuels. In addition, the obtained values of the measured parameters were related to the normative values indicated in ISO 8217:2024 [38] in the section on distillation fuels and the requirements of the Ministry of Economy of Poland RMG [40]. In addition, with regard to sulfur content, the requirements indicated in Annex VI of the MARPOL Convention [39] are indicated. Sulfur content, water content, metal content, and impurities content, as well as total sediment by hot filtration, carbon residue, and ash content, were described by linear models in connection with the directly proportional share of these components in the blend depending on the mass share of pyrolysis oil in the blend with diesel oil, which is a direct result of the composition of the base oils used to make the blends. The possibility of using linear models for these parameters has found support in the literature [66,67]. In the case of lubricity, defined as the average diameter of the wear footprint $WS_{1.4}$, the present authors proposed two approximating models: a linear model with a moderately good fit and a nonlinear hyperbolic model that provides a very good fit. The linear model for the $WS_{1.4}$ index has previously been successfully used by the present authors in evaluating the lubricity of lubricating oil blends and diesel oil of known composition [49]. The quality of the fit was evaluated for each of the developed models using the coefficient of determination R^2 .

3. Results and Discussion

3.1. Sulfur Content in the Fuels Under Study

The sulfur content of the fuels tested is shown in Figure 1. The blue dotted line indicates a function that approximates the sulfur content C_S (% m/m) for fuels containing different amounts of recycled oil C_{RF} (% m/m) in the diesel blend. The figure also shows permissible maximum sulfur content values according to selected standards and regulations.

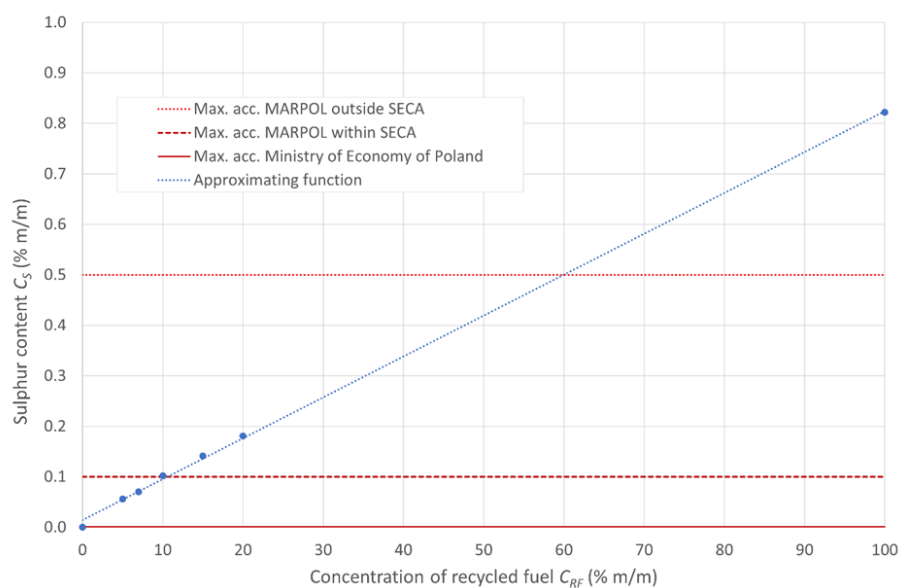


Figure 1. Sulfur content in the fuels under study (limits are based on the normative documents [39,40]).

The equation of the approximating function, as shown in Figure 1, has the following form:

$$C_S = 0.0081C_{RF} + 0.0143, \quad (1)$$

which shows a very good fit, as evidenced by the high value of the coefficient of determination $R^2(C_S) > 0.999$.

According to RMG guidelines, the sulfur content must be no greater than 10 mg/kg. None of the fuels containing TPO in the formulation meet this requirement. According to [38] sulfur content is up to statutory requirements. The MARPOL Convention in Annex VI details these requirements. When using deSOx exhaust gas desulfurization systems (scrapers in the exhaust gas system), the permissible sulfur content is 3.5%, while standard systems require the use of low sulfur fuels with 0.5% m/m sulfur content for global shipping and ultra-low sulfur content with 0.1% m/m sulfur content for shipping in sulfur emission control area (SECA) zones. Fuel blends with up to 10% m/m recycled oil in diesel meet all MARPOL requirements for SECA zones. Moreover, for concentrations of up to 20% m/m of pyrolysis oil in the fuel blender, all the tested fuels meet the requirements for global shipping outside the sulfur emission control areas (SECA zones).

3.2. Water Content in the Fuels Under Study

The water content C_w (% m/m) of the tested mixtures is shown in Figure 2. The permissible maximum water content values according to selected standards and regulations are plotted in Figure 2.

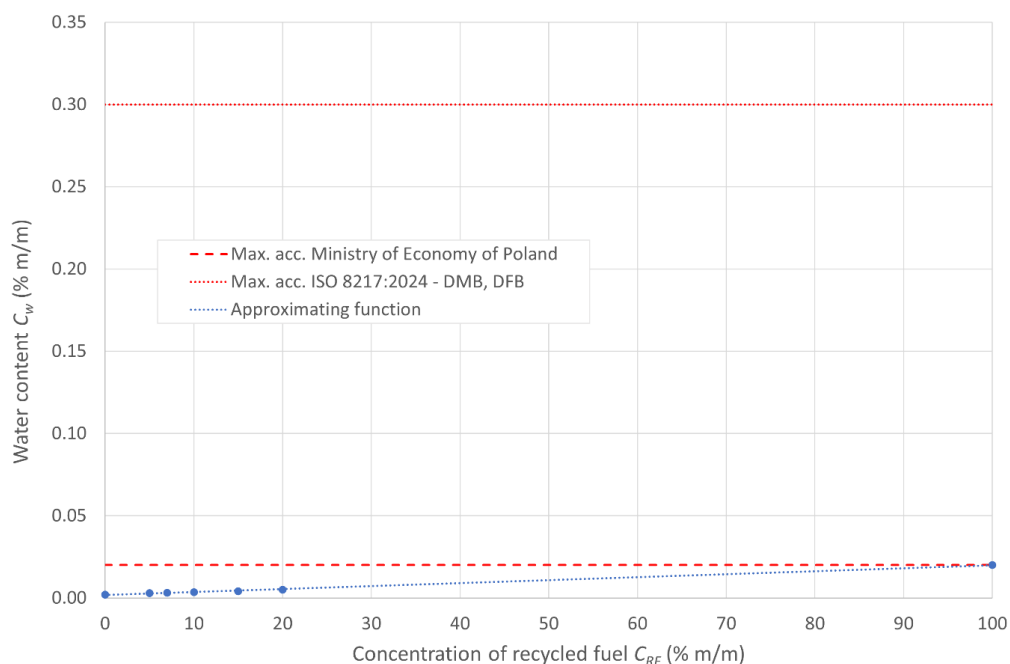


Figure 2. Water content in the fuels under study (limits are based on the normative documents [38,40])

In Figure 2, the blue dotted line indicates the linear function approximating the results of the measurement, i.e.,

$$C_w = 0.0002C_{RF} + 0.0017, \quad (2)$$

which shows a very good fit, as evidenced by the high value of the coefficient of determination $R^2(C_w) > 0.997$.

The water content of the fuels tested increases linearly with increasing recycled oil concentration in the blend; nevertheless, over the entire range of concentrations tested, the water content is within the permissible range indicated by the RMG, which is 0.02% m/m. In contrast, according to [38], the permissible water content must be <0.3% v/v for DMB and DFB grade fuels; for other fuels with lower viscosities, the standard does not indicate a value.

3.3. Lubricity of the Fuels Under Study

The lubricity of the tested fuels is shown in Figure 3, where the recorded and permissible maximum values of the content of the corrected wear scar $WS_{1.4}$, which accords with the standards and regulations considered in the experiment, are plotted. With an increase in recycled oil content in the blend, the corrected average wear footprint decreases, so the lubricating properties of fuel blends improve. This may be due to both the complex hydrocarbon composition of recycled oil and the increasing sulfur content of fuel blends with higher recycled oil contents, as sulfur exhibits natural lubricating properties.

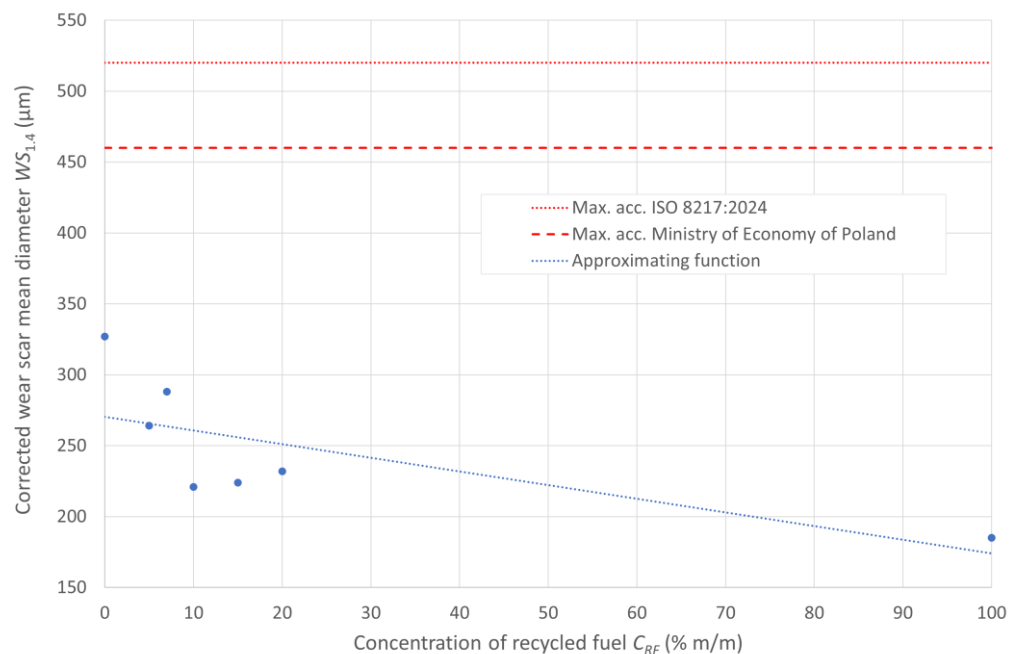


Figure 3. Lubricity of the fuels under study (limits are based on the normative documents [38,40])

In Figure 3, the blue dotted line indicates the linear approximating function of the form:

$$WS_{1.4} = -0.9621C_{RF} + 2170.29, \quad (3)$$

which shows a moderately good fit to the empirical data, as evidenced by a coefficient of determination equal to $R^2(WS_{1.4}) > 0.494$.

Relationship (3) is the simplest model that can be refined. Since the nature of changes in the value of $WS_{1.4}$ as a function of C_{RF} shows features of an exponential function, the present authors undertook the task of finding a model with a better fit that could be used in future studies. The proposed complex approximating function for the empirical data obtained is of the form:

$$WS_{1.4} = 176.7302 + \frac{150.3915}{1 + \left(\frac{C_{RF}}{8.517366}\right)^{1.082307}}. \quad (4)$$

The model described by Equation (4) shows a very good fit, as evidenced by the coefficient of determination $R^2(WS_{1.4}) > 0.878$.

According to [38] the permissible lubricity defined as the maximum value of corrected wear scar diameter $WS_{1.4}$ at 60 °C is 520 μm . All the tested mixtures and pure recycled fuel meet these requirements. The guidelines of the RMG are stricter, for which the maximum allowable wear scar is 460 μm . All the tested fuels meet the requirements in question in terms of their ability to form a boundary guard.

3.4. Impurities in the Fuels Under Study

The ash residue X_A (% m/m), coking residue with 10% distillation residue X_{CR} (% m/m), mechanical insoluble impurities content X_C (mg/kg), and total sediment by hot filtration X_S (% m/m) are shown in Figures 4–7, respectively. These figures also show the permissible values indicated in the standards and regulations analyzed in the experiment. According to the RMG and ISO 8217 guidelines, the permissible maximum residue after coking is 0.30% m/m, and the permissible maximum residue after ashing is 0.010% m/m. In contrast, the permissible content of insoluble mechanical impurities according to the RMG document is 24 mg/kg, equivalent to 0.0024% m/m, while ISO 8217 does not refer to insoluble impurities since it only indicates the permissible value of total sediment by hot filtration. The latter only applies to distillate fuels with the worst properties of the DMB and DFB grades, and the permissible value for these fuels is 0.1% m/m.

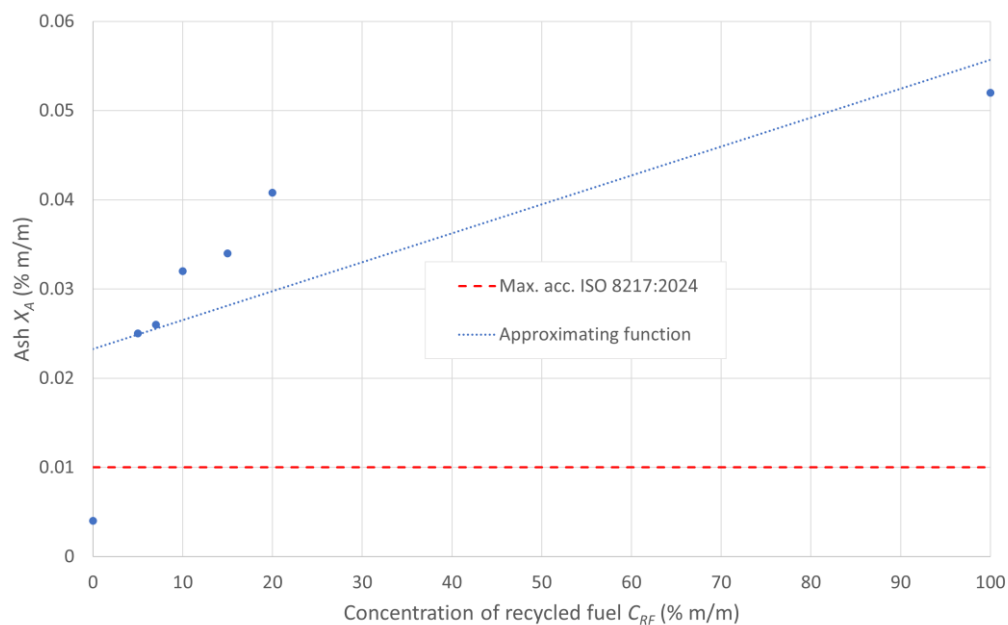


Figure 4. Ash residue of the fuels under study (limits are based on the normative documents [38])

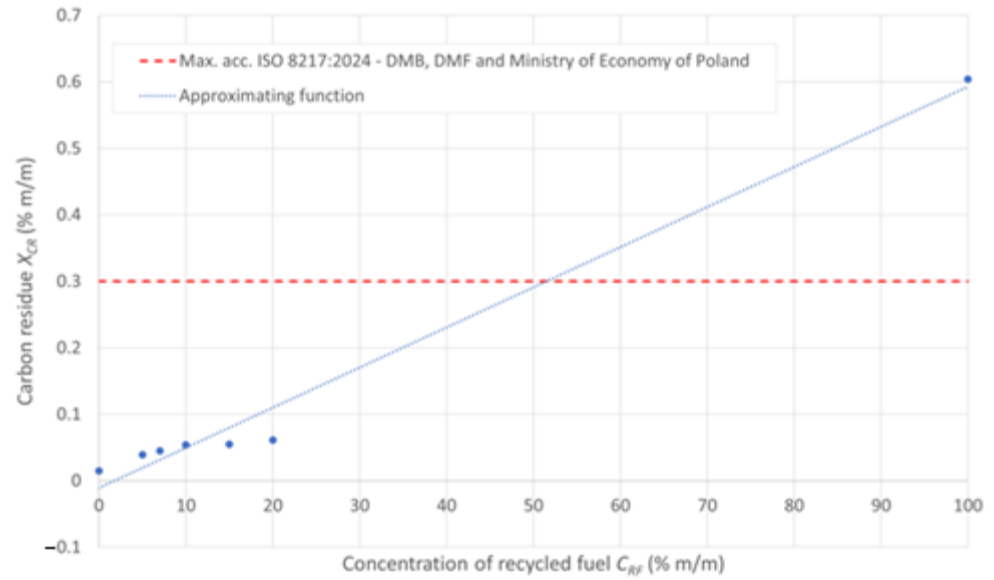


Figure 5. Residue after coking of the fuels under study (limits are based on the normative documents [38,40]).

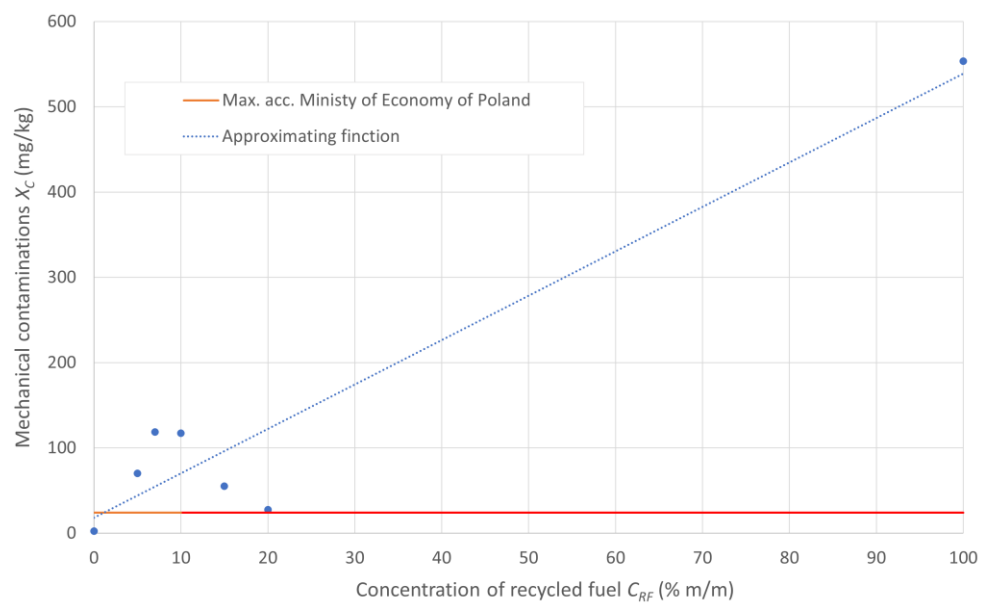


Figure 6. Mechanical contamination of the fuels under study (limits are based on the normative documents [40]).

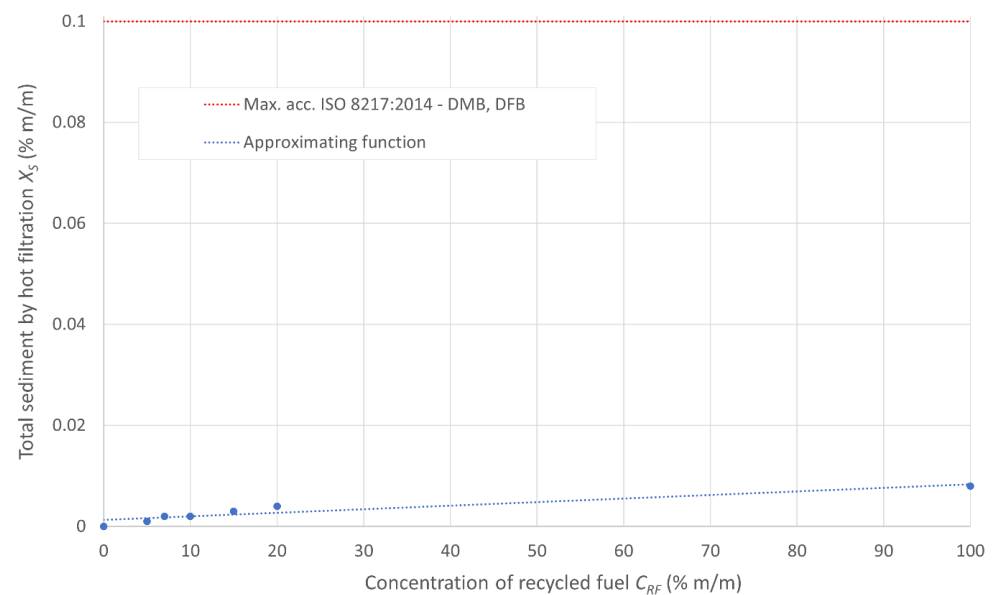


Figure 7. Total sediment by hot filtration of the fuels under study (limits are based on the normative documents [38]).

The blue dotted lines in Figures 4–7 display the approximating curves in the form of linear functions, which are described by the following formulas:

$$X_A = 0.0003C_{RF} + 0.0233, \quad (4)$$

$$X_{CR} = 0.0055C_{RF}, \quad (5)$$

$$X_C = 5.2063C_{RF} + 18.07, \quad (6)$$

$$X_S = 7 \cdot 10^{-5}C_{RF} + 0.0013. \quad (7)$$

Models (5)–(7) show a good to very good fit to the empirical data as evidenced by the values of the coefficient of determination, which for the aforementioned equations are $R^2(X_A) > 0.571$, $R^2(X_{CR}) = 0.987$, $R^2(X_C) > 0.915$, and $R^2(X_S) > 0.893$, respectively.

The authors determined the measurement uncertainty values based on the calibration certificates of the measuring instruments used, except for the sediment content value by hot filtration, for which the reproducibility value was calculated according to the formula specified in the standard under which the measurement was performed. Due to the low uncertainty values of most of the measured parameters compared to the determined parameter values, uncertainty bars were not included in the graphs presented in Figures 1–7. A summary of the calculated measurement uncertainty values for the analyzed parameters is shown in Table 4.

Table 4. Summary of the uncertainties of the obtained measurement results for each parameter.

Parameter	Symbol *	Unit	Concentration of Recycled Fuel C_{RF} (% m/m) $\pm 0.0023\%$ m/m						
			0	5	7	10	15	20	100
Sulfur content	$U(C_S)$	% m/m	0.0070	0.0089	0.0094	0.0105	0.0118	0.0132	0.0351
Water content	$U(C_w)$	% m/m	0.0023	0.0025	0.0025	0.0025	0.0026	0.0028	0.0050
Lubricity (HFRR wear scar diameter) @ 60 °C	$U(WS_{1.4})$	μm	30.7	24.8	27.1	20.8	21.0	21.8	17.4

Coke residue (from 10% distillation residue)	$U(X_{CR})$	% m/m	0.0405	0.0428	0.0433	0.0442	0.0443	0.0448	0.0959
Ash residue	$U(X_A)$	% m/m	0.0025	0.0030	0.0030	0.0031	0.0032	0.0033	0.0036
Contaminant content/total sediment by hot filtration	$U_R(X_s)$	% m/m	0.0000	0.0055	0.0078	0.0078	0.0095	0.0110	0.0156
Content of mechanical insoluble impurities	$U(X_C)$	mg/kg	1.3772	10.7171	17.4018	17.1934	8.6236	4.8300	77.4056

* U —uncertainty, U_R —reproducibility.

The elemental composition of the tested fuels is shown in Figure 8. It can be observed that, with an increase in the concentration of pyrolysis oil in the mixture with diesel fuel, the content of nickel, lead, and tin significantly increases, which indicates that the pyrolysis oil used to prepare the tested fuel mixtures is contaminated with these metals.

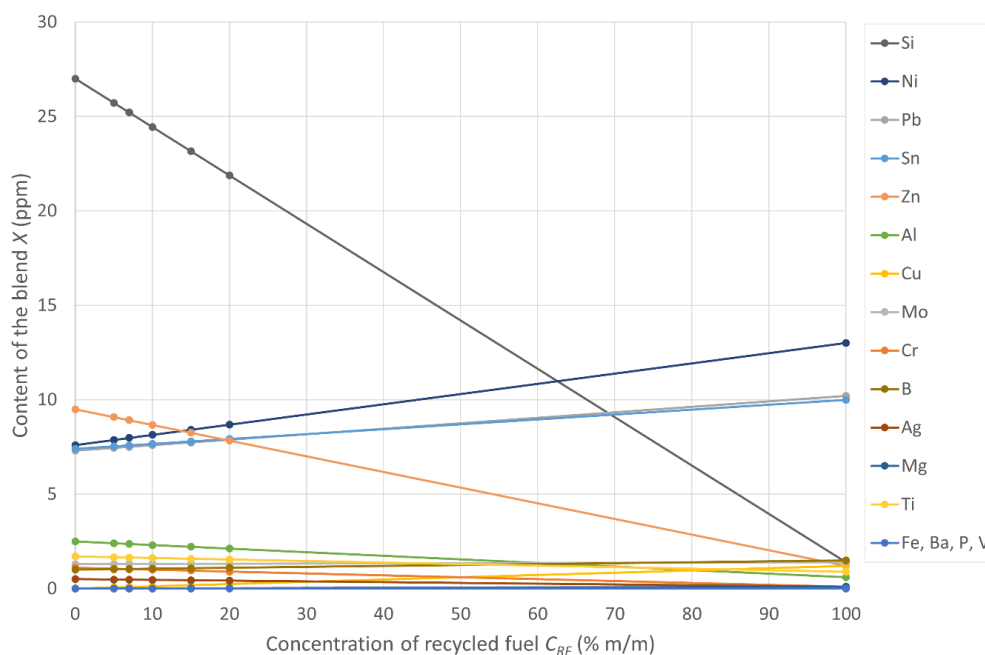


Figure 8. Elemental composition of tested fuels as a function of pyrolysis oil content in the diesel blend.

In turn, the content of silicon and zinc, derived from the diesel oil used to make the mixtures, decreases. Other labeled elements, including vanadium, that are responsible for high-temperature corrosion show little variability and remain low at <3 ppm.

All of the fuels tested in the recycled oil concentration range up to 20% m/m meet the requirement for coking residue. All the fuels meet the requirements for total sediment by hot filtration according to, [38] while none of the tested fuel blends meet the requirements for acceptable ash content and insoluble mechanical impurities content. Thus, this indicates that the fuels tested need to undergo additional treatment to purify them.

3.5. Summary of the Obtained Results

A summary of the conducted research and a reference of the recorded values of the analyzed indicators in relation to the normative values is presented in Table 5. Here, a plus symbol (+) indicates that the fuel meets the requirements for the value of a specific

parameter within the permissible limits, while a minus symbol (–) signifies parameters that are outside the permissible values.

Table 5. Aggregate summary of the tested fuels' compliance with the limit requirements indicated in the selected documents.

Require- ments	TPO Content of the Tested CRF Blende (% m/m)	0	5	7	10	15	20	100
ISO 8217:2024	Sulfur content, C_S	+	+	+	+	+	+	+
	Water content, C_w	+	+	+	+	+	+	+
	Lubricity, $WS_{1.4}$	+	+	+	+	+	+	+
	Ash, X_A	+	–	–	–	–	–	–
	Carbon residue, X_{CR}	+	+	+	+	+	+	–
	Total sediment by hot filtration, C_S	+	+	+	+	+	+	+
Ministry of Economy of Poland	Sulfur content, C_S	+	–	–	–	–	–	–
	Water content, C_w	+	+	+	+	+	+	+
	Lubricity, $WS_{1.4}$	+	+	+	+	+	+	+
	Ash, X_A	+	–	–	–	–	–	–
	Carbon residue, X_{CR}	+	+	+	+	+	+	+
	Mechanical contamination, X_C	+	–	–	–	–	–	–
MARPOL, Annex VI	Sulfur content C_S (within SECA)	+	+	+	+	–	–	–
	Sulfur content C_S (outside SECA)	+	+	+	+	+	+	–
	Sulfur content C_S (with deSO _x system)	+	+	+	+	+	+	+

The tested fuels meet most of the legal requirements, and their mismatch with the applicable requirements relates to exceeding the permissible minimum values of sulfur and ash content and the content of mechanical impurities. These components are one of the products of pyrolysis and should be removed before fuels are used according to specific guidelines. The sulfur content for marine applications is from the limits of the guidelines indicated in MARPOL for fuels with up to 10% TPO, which can be used in all maritime areas. In this case, there is no need to install scrubbers in the exhaust gas systems, and such fuels can be used directly to power engines. For land applications, the fuels analyzed require desulfurization or use in systems with deSO_x systems in the exhaust gas systems. In turn, the content of non-combustible substances (separated in the form of ash) can intensify the processes of abrasive wear and corrosion of components (vanadium-sodium high-temperature corrosion) of the engine, so it is necessary to subject the fuel to appropriate treatment aimed at reducing the content of impurities.

4. Conclusions

Studies have shown that diesel blends with the addition of tire recycled oil (TPO) have the potential to be used as an alternative fuel. Blends containing up to 20% TPO by weight meet most of the requirements indicated in [38] and the MARPOL Convention. This indicates their potential usefulness as additives to conventional fuels, but certain limitations, such as ash content and compliance with sulfur regulations that may differ from environmental requirements, must be taken into account.

In terms of sulfur content, fuel blends with up to 10% TPO meet MARPOL requirements for fuels used in SECA zones, where the maximum allowable sulfur content in the

fuel used is 0.1% m/m, while fuels with up to 20% TPO meet MARPOL requirements for fuels used in global shipping outside SECA zones, where the maximum allowable sulfur content in the fuel used is 0.5% m/m. Such fuels in the indicated areas can be used without additional sulfur reduction systems such as scrubbers, making them an attractive solution from an economic point of view. At higher than 20% m/m TPO contents in blends (according to the approximation equation, above 60% m/m TPO content), it is necessary to use deSO_x technology on ships (in this case, the allowable fuel sulfur content is 3.5% m/m). An alternative is to desulfurize the pyrolysis oil used to prepare the fuel blends.

One of the key technical parameters of fuels is their lubricity. Tests have shown that all the analyzed blends meet the requirements for the maximum diameter of the wear scar, i.e., 520 μm according to [38] and 460 μm according to RMG guidelines. Moreover, increasing the TPO content in the blends has a positive effect on the lubricity of the fuel, which is presumably due to the presence of sulfur and the complex hydrocarbon composition of TPO. Better lubricity translates into increased durability of engine components in contact with the fuel, such as injectors and fuel pumps.

Despite the advantages, TPO fuel blends have limitations. All the blends tested with pyrolytic oil content in the range of 0–20% m/m meet the requirements for coking residue and total sediment by hot filtration; however, the ash content exceeds normative limits. This implies a need for additional fuel treatment to reduce non-flammable substances that can contribute to increased wear and corrosion of engine components. In terms of water content, the blends meet acceptable [38] and [40], indicating that they are of adequate quality in this regard. Water in industrial and marine installations can be removed during operation by filtration, centrifugation, and gravity sedimentation.

In summary, fuels containing up to 20% TPO after ash removal appear to be a valuable alternative as marine transportation fuels outside SECA zones, where they can be used without additional sulfur reduction systems. However, for more demanding applications, such as onshore power generation and land transportation, further treatment of the tire pyrolysis oil, including its desulfurization and filtration, is needed to meet the relevant requirements for emissions in the exhaust gas and the negative effects of the fuels and their combustion products on the structural components of the internal combustion engine and cooperating equipment. Another option is the possibility of using the tested fuels to power boilers equipped with appropriate flue gas cleaning systems.

The use of fuels with TPO will require the use of appropriate purification technologies to reduce the content of, for example, ash and other undesirable components. Future research should focus on improving these parameters, which will make these fuels more attractive both economically and environmentally.

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Abbreviations

C_S	sulfur content in the fuels under study
C_{RF}	mass percentage of recycled oil in the diesel blend
C_w	water content in the fuels under study
D100	pure diesel oil without FAME additives
deSO _x	flue gas desulfurization system
DFA, DFB, DFZ, DMA	categories of distillation fuels indicated in the standard
DMB, DMZ, DMX	[38]marked as ISO-F-...
EU	European Union
FAME	fatty acid methyl esters
HC	hydrocarbons with general designation
HFRR	high-frequency reciprocating rig
ISO	International Organization for Standardization
MARPOL	International Convention for the Prevention of Pollution from Ships
NO _x	generic determination of NO and NO ₂ nitrogen oxides
RF	index for the parameters measured or calculated for recycled fuel TPO
RMG	Regulation of the Ministry of Economy of Poland on the properties of fuels
SECA	Sulfur Emission Control Areas
SO _x	general designation for sulfur oxides SO ₂ and SO ₃
t_{CFPP}	cold filter plugging point temperature
t_{FP}	flash point temperature
TPO	tire pyrolysis oil
U	uncertainty
U_R	reproducibility
W	lower heat value
$WS_{1.4}$	average diameter of wear scar during HFRR lubricity test corrected to a reference pressure of 1.4 kPa
X_A	ash residue
X_{CR}	coking residue with 10% distillation residue
X_S	total sediment by hot filtration
ν_{100}	kinematic viscosity at a reference temperature of 100 °C
ν_{40}	kinematic viscosity at a reference temperature of 40 °C
ρ_{15}	density at a reference temperature of 15 °C

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