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The Research on Characteristics of CI Engine Supplied with Biodiesels from Brown and Yellow Grease

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Abstract: The effect of three kinds of fuels used to supply a diesel engine on its characteristics, fuel consumption, and emissions was studied. The fuels comprised pure diesel, a blend of diesel with 6% of methyl ester of yellow grease in the form of rapeseed oil, and a blend of diesel with methyl ester of brown grease in the form of goose fat. The chromatographic analysis was conducted for these fuels, and the results are presented. Two tests, comprising measurement of fuel consumption and engine emissions, were conducted on a vehicle with a diesel engine operating under zero load and under full load. The engine's characteristics, including both power and torque versus speed, were determined under full engine load. The results of these tests are presented in this paper. The results indicated that the use of different methyl ester-based biodiesel blends with the same content of diesel to supply the diesel engine resulted in different fuel consumption and emissions of the engine not only in comparison to the supply of pure diesel but between biodiesels analyzed.

Keywords: biodiesel; yellow grease; brown grease; diesel engine; fuel consumption; engine emission

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1. Introduction

Increasing energy demand and the harmful environmental effects of fossil fuels make biofuels, both solid ones [1,2] and liquid ones [3], an interesting alternative. Liquid biofuels, particularly those derived from inedible biomass, are promising renewable energy sources for transportation. This is because they are usable within current infrastructures and need fewer technological advances than electric vehicles and nuclear power. The negative effects of biofuels on food security and production strongly depend on the type of feedstock used in biofuel production. Further studies on methods that decrease their level of harmfulness are needed [3].

Nowadays, the demand to replace commonly utilized diesel with alternative fuels, particularly the bio-derived ones, has become increasingly visible [4,5].

Biodiesel is a renewable, biodegradable fuel manufactured domestically from vegetable oils, animal fats, or recycled restaurant grease. Biodiesel meets both the biomass-based diesel and overall advanced biofuel requirement of the Renewable Fuel Standard related to a minimum volume of renewable fuels contained in transportation fuel [6]. Biodiesel in its pure form is known as "neat" biodiesel. A biodiesel blend is pure biodiesel blended with petrodiesel with the notation of Bxx, where the xx indicates the volumetric amount of biodiesel in the blend, commonly varying from B2 to B20. According to [7], biodiesel is often blended with petroleum diesel in a ratio ranging from 5% to 20% (B5-B20).

Renewable hydrocarbon biofuels comprise renewable gasolines, renewable diesels, and sustainable aviation fuels (SAF) produced from biomass sources through a variety of biological, thermal, and chemical processes via various technology pathways, including traditional hydrotreating, biological sugar upgrading, catalytic conversion of sugars, gasification, pyrolysis, and hydrothermal processing [8].

Renewable diesel, so-called 'green diesel', is a biomass-derived transportation fuel suitable for use in diesel engines. It meets the ASTM D975 specification for petroleum in the United States and EN 590 in Europe. It is chemically identical to diesel and can be used in existing diesel engines [9].

The goal of our study was to compare the effect of supplying an engine with pure diesel fuel and two blends, one a mixture of diesel and 6% biodiesel in the form of MEYG—methyl ester of yellow grease (rapeseed oil) and the other MEBG—methyl ester of brown grease (goose fat), on the characteristics, fuel consumption, and emissions of the diesel engine in the chosen vehicle.

2. Feedstocks for Biodiesel

According to [10], there are six EPA-approved biodiesel and renewable diesel production feedstocks. These are soybean oil, yellow grease, distillers corn oil, animal fats, canola oil, and camelina. As of September 2017, their respective content in the biomass-based diesel market was about 46%, 15%, 15%, 13%, 11%, and below 1%.

Bartha-Vári et al. [11] noted that biodiesel could be produced from edible oils, including soybean and palm oil, and non-edible oils, such as cooking oils and algal or fungal oils.

Edible oils are cheaper for biodiesel production in comparison to algal oils [12].

The triglycerides of edible oils comprise various fatty acids, including mostly (9Z)-9-octadecenoic acid (oleic acid, OA), followed by (9Z,12Z)-9,12-octadecadienoic acid (linoleic acid, LA), myristic, palmitic, and stearic acids, respectively. Biodiesel can also be produced from the fatty phase of wastes (brown grease—BG) or palm fatty acid distillate (PFAD) [13].

According to Gebremariam and Marchetti [14], fresh vegetable oils are used for biodiesel production on an industrial scale. However, Mansir et al. [15] stated that most biodiesel production costs resulted from utilizing fresh edible oils as feedstock.

Therefore, optional, cheaper sources of lipids were proposed, including waste cooking oil, non-edible Jatropha, algae, tamarind seed oil, municipal sewage sludge, and recycled grease trap waste [16–19].

Elgharbawy et al. [20] noticed that biodiesel feedstocks vary between edible oils such as sunflower, soybean and coconut oil and non-edible oils such as Jatropha, jojoba, and used cooking oil.

Grzelak and Zoltowski [21] proposed the use of waste oils to produce hydrogenated vegetable oils (HVOs) and described an existing biorefinery plant in Venice producing HVO fuel. They presented the parameters of such a biofuel and compared them with the parameters of diesel and biodiesel containing FAMEs applied as a 7% additive to diesel oil.

3. Technologies for Biodiesel Production

The most popular biodiesel production method at a higher scale is the alkali-catalyzed transesterification of fresh vegetable oils [14].

According to Elgharbawy et al. [20], biodiesel is often obtained from vegetable oil via a transesterification reaction, substituting the organic group (alkyl) of an alcohol with the organic group of a triglyceride, producing FAME and glycerol. The authors reviewed four types of transesterification processes, acid-catalyzed, alkaline-catalyzed, enzyme-catalyzed, and non catalyzed supercritical methanol. They noticed that the alkaline-catalyzed method is the most utilized process due to it having the fastest reaction, the highest yield, the mildest reaction condition, and the lowest cost, corrosiveness, and toxicity.

As reported in [22,23], biodiesel can be produced via transesterification and esterification. Transesterification results in the formation of alkyl esters of FFAs and glycerol as a byproduct of the reaction between mono-, di-, or triglycerides and alcohol. During

esterification, a reaction between alcohol and FFA takes place, resulting in the formation of alkyl esters.

As methanol and ethanol are used in such reactions [22], both methyl and ethyl esters are found to be biodiesels [24].

The activation of transesterification and esterification reactions is realized by agitation and heating [25].

Acid catalysis is preferred [26], but it has a longer duration (over 12 h), needs higher temperatures (120–250 °C), and a larger amount of catalyst (here of acid type) compared to basic catalysis. Because sulfuric acid is insensitive to small amounts of water, it is usually applied as a catalyst in the esterification of FFAs.

As homogeneous aggressive catalysts cause equipment corrosion, they can be replaced by heterogeneous basic or acidic catalysts [13].

4. Research on Biodiesel from Yellow Grease

Several studies have been conducted on biodiesels obtained from various yellow greases.

Panchal et al. [27] studied the one-step process of producing biodiesel from yellow fat by kinetic transesterification of yellow grease with dimethyl carbonate in a molar ratio (1:5), using a CH_4O_3S catalyst, reaction temperature equal to 708 °C, time of 45 min, and mixing speed equal to 125 rpm. The maximum yield of biodiesel with yellow fat was achieved at 94%. The biodiesel properties tested, such as kinematic viscosity at a temperature equal to 408 °C, specific gravity at a temperature equal to 258 °C, flash point, pour point, cloud point, and corrosion grade of the copper strip, were in accordance with the ASTM D6751–02 biodiesel quality standards.

Ortiz–Martínez et al. [28] investigated the transesterification reaction of Pongamia pinnata oil, also known as Karanja oil, in supercritical methanol in a one-step catalyst-free process. Triglyceride (TG) conversion and the yield of FAMEs at an alcohol-to-oil molar ratio of 43:1 was investigated in the temperature range of 250–350 °C, under the pressure of 12–43 Mpa, and in a time range of 15–90 min, respectively. They also studied the evolution of monoglycerides (MG) and diglycerides (DG) and the thermal decomposition of fatty acid chains for the mentioned reaction regimes. The best conditions for such a reaction are a temperature of 300 °C and a reaction time of 90 min, allowing almost complete triglyceride conversion. Then, a high level of thermal disintegration occurred from 325 °C, mainly due to the degradation of polyunsaturated fatty acid methyl esters. The highest degree of thermal disintegration of 38% took place at 350 °C at the end of reaction time.

Goembira and Saka [29] studied biodiesel production from Pongamia pinnata oil using an interesterification process called the one-step supercritical methyl acetate method under reaction conditions of 300 °C/20 MPa/45 min/42 M ratio in methyl acetate to oil. The addition of 10 wt.% aqueous acetic acid allowed conducting the interesterification process under the mentioned reaction condition. It achieved the highest yield of 96.6 wt.% FAME and 11.5 wt.% triacetin (total 108.1 wt.%). Both products were miscible, and their biodiesel properties agreed with biodiesel standards.

Özçelik et al. [30] investigated the effects of biodiesel (B100) obtained from safflower oil in the transesterification process and its two blends with Eurodiesel (10:90%—B10) and (20:80%—B20) on the characteristics of a four-stroke, common-rail fuel system, water-cooled, four-cylinder diesel engine. They found that engine power values obtained with Eurodiesel fuel, biodiesel, and their blends were close to one another at all engine speeds. The fuel consumption was slightly enhanced for the engine supplied with biodiesel and its blends compared to the supply with Eurodiesel fuel.

Syamsuddin and Hameed [31] conducted a synthesis of glycerol free-methyl esters (FAME) for the transesterification of Jatropha oil utilizing dimethyl carbonate (DMC) as a methylating agent over heterogeneous Ca–La mixed-oxide catalyst. The optimal reaction conditions occurred at a 4:1 molar ratio of DMC to oil, 150 °C reaction temperature, 120 min reaction time, and 3 wt.% of catalyst loading, allowing obtaining conversion and yield of 99.84%.

Gaurav et al. [32] suggested the use of catalytic distillation (CD), combining a catalytic reaction and separation via distillation in the same distillation column for biodiesel production from yellow grease comprising both triglyceride and free fatty acid. They emphasized an advantage of CD in comparison to a conventional biodiesel process due to the limited number of distillation columns, waste streams, and greenhouse gas generation.

Duda et al. [33] studied the performance and emission characteristics of a compression ignition engine equipped with a common rail injection system. The engine was fueled with diesel and diesel–biodiesel blends containing 25% and 50% (by volume) of methyl esters of rapeseed oil obtained from the single-stage transesterification process. The experiments were conducted on a medium-duty, turbocharged, inter-cooled, common rail direct injection (CRDI) diesel engine operating at a speed of 1500 rpm and mid-load range from 100 Nm to 200 Nm. They found that the introduction of the mentioned renewable component to a fuel blend usually improved performance parameters and lowered engine emissions.

5. Research on Biodiesel from Brown Grease

Fewer studies have been conducted on biodiesel obtained from various brown greases.

According to [34], on 3 December 2021, the International Sustainability and Carbon Certification (ISCC) stated that the category of brown grease or grease trap fat "shall exclusively be used for material that is removed from grease traps" and "this category shall not be used for material that is removed from the sewage system". This definition excludes edible oil waste collected from sewers from being classed as brown grease. Oil removed from sewers is instead covered under the sewage sludge category, which was expanded to include fats, oils, and grease (FOG) from the sewage system, while the separate sewage system FOG category was deleted.

Kolet et al. [35] stated that brown grease is a mixture of oils, fats, solids, and detergents from food industry wastes that are captured in grease traps. Brown grease contains oils and fats convertible into biodiesel. However, the high concentration of free fatty acids in brown grease excludes the application of conventional biodiesel production schemes. The authors elaborated a scheme for biodiesel production from brown grease. They studied conditions for the effective separation of a fat phase from brown grease and determined the composition of a fatty phase for several grease traps. They conducted esterification and transesterification of brown grease lipids with methanol, with accompanied catalysts of the Lewis acids BF_3 and $AlCl_3$. The reaction was activated by ultrasound. They found that biodiesel was obtainable from brown grease via esterification and transesterification within several minutes under ultrasonic activation at room temperature.

Research from the same group, also in [13], combined the application of Lewis catalysts with ultrasound activation to the scheme of biodiesel production from FFAs.

Tran et al. [36] reviewed recent achievements in the production of biodiesel from grease trap waste (GTW).

According to Hums et al. [37], thickened and dewatered Grease Trap Waste (GTW) can be upgraded to brown grease via heating and settling. Using a bubble column reactor, brown grease can be converted into crude biodiesel. Such a conversion process is realizable at ambient pressure and low temperatures, using readily available industrial chemicals. Purification of the reaction products is conducted via distillation and adsorption, resulting in weakening sulfur content, but such a scheme is still slightly effective. After purification, the biofuel typically contains approximately 25 ppm–50 ppm sulfur, which is still over the required specification. Interestingly, it was mentioned that laboratory-scale desulfurization experiments using reactive desulfurization and enhanced adsorption strategies allowed reducing sulfur content to 10–15 ppm.

Zheng et al. [38] studied a potential biodiesel feedstock in the form of larval grease extracted from yellow mealworm beetles (*Tenebrio molitor* L.) (YMB), a post-harvest scavenger, fed with decayed vegetables for 9 weeks before extraction of its grease. Interestingly, 34.2 g of biodiesel was obtained from 234.8 g of dried YMB larval biomass. The YMB biodiesel comprised various fatty acids, including linolenic acid (19.7%), palmitic acid

(17.6%), linoleic acid (16.3%), and stearic acid (11.4%). The YMB biodiesel features met the standard EN 14214, including ester content (96.8%), density (860 kg/m^3), flash point (127 °C), cetane number (58), water content (300 mg/kg), and methanol content (0.2%).

Spiller et al. [39] characterized two brown grease samples captured from local grease traps or wastewater facilities. Raw brown grease was fermented using Clostridium butyricum to produce butyric acid. A yield of 0.55 butyric acid/g sugars was obtained, also confirming the conversion of the glycerol and lactic acid. Hexane extraction of the fermentation broth allowed obtaining an 81.3% recovery of lipids.

Fan et al. [40] converted brown grease to biodiesel FAME. It was created in a two-stage reaction comprising esterification and transesterification using Novozym 435 in a solvent-free medium. They studied the effects of methanol amounts and enzyme concentration on the first-stage reaction and the operational stability of Novozym 435 in the two-stage reaction. They found that the addition of biodiesel into the reaction system prior to the two-stage reaction prevented the lipase from deactivation. The latter was induced by excess amounts of methanol. They obtained contents of FAME above 95 wt.%, even after 15 cycle reactions.

The research group Duda et al. [33] also studied the performance and emission characteristics of the aforementioned diesel engine supplied with diesel–biodiesel blends containing 25% and 50% share (by volume) of methyl esters of turkey lard obtained from the single-stage transesterification process. They found that the addition of the mentioned renewable component to a fuel blend improved performance parameters and lowered engine emissions in most cases studied.

6. Materials and Methods

During the present study, three kinds of fuel were utilized, including:

- pure diesel fuel (as delivered);
- a blend of diesel with 6% of biodiesel obtained from yellow grease, more specifically in the form of methyl ester of rapeseed oil (as delivered);
- a blend of diesel with 6% of biodiesel obtained from a brown grease, more specifically in the form of methyl ester of goose fat obtained via transesterification process described further.

These fuels were utilized to supply a diesel engine for the chosen vehicle. The vehicle's fuel consumption and emissions under both zero and full-load of the engine were investigated.

6.1. Goose Fat Transesterification

6.1.1. Reagents and Equipment

For the transesterification process, the following reagents were used:

- goose lard;
- sodium methoxide solution.

For the transesterification process, the following equipment was utilized:

- round bottom flask with a capacity of 100 and 250 mL;
- reflux cooler;
- magnetic stirrer;
- water bath;
- thermometer;
- manifold with a capacity of 250 mL;
- measuring cylinder;
- beakers;
- conical flask with a stopper;
- glass funnel.

6.1.2. Methodology

To prepare the methanolic catalyst solution, 3.36 g of solid NaOH were weighed and dissolved in 36 mL of methanol in a conical flask with a capacity of 100 mL.

Next, 120 g of goose lard was introduced into a rounded flask with a capacity of 250 mL fitted with a magnetic rod and a reflux condenser. This was placed in a water bath at a temperature of about 50 °C (monitored with a thermometer), and the catalyst solution prepared in advance was introduced. The blend was stirred with a magnetic stirrer for 60 min. The reaction blend was then transferred to a separating funnel, and 50 mL of 10% HCl was added, mixed, and allowed to separate (about 10–20 min). The lower water–glycerin layer was separated, and the upper oily layer was washed twice with distilled water (2 × 50 mL). Washing was done carefully by slightly tilting the funnel to avoid the formation of stable emulsions.

The procedure was repeated to obtain the amount of biodiesel needed for mixing with pure diesel to obtain the estimated amount of fuel necessary to supply the diesel engine during the investigation. To be more specific, the amount of fuel had to be sufficient to supply the tested engine during two measurements of its fuel consumption during operation at a rotational speed of 1500 rpm and separately at its zero and its full load. Therefore, it was twice the volume of an additional 1 L transparent plastic fuel tank. Since the amount of biodiesel in the blend with diesel was to be 6%, the required amount of produced methyl ester of goose fat was about 200 mL.

6.2. Chromatographic Analysis of Fuels Used

Qualitative analysis of samples I–III (I—pure diesel fuel sample; II—diesel with 6% of methyl ester of rapeseed oil; III—diesel with 6% of methyl ester of goose fat) was performed using a Hewlett Packard series 5890 chromatograph (Agilent Technologies) coupled with a Hewlett Packard series 5972 mass spectrometer. A DB-5MS capillary column (30 m, 0.250 mm) was used. During the measurement, the following GC column temperature program was used: 40 °C for 4 min, then the temperature was increased to 70 °C at a rate of 4 °C/min, then increased to 250 °C at a rate of 20 °C/min and held for 10 min. The injection port and detector temperatures were 250 and 200 °C, respectively. Helium of purity 5.0 was used as the carrier gas. The range of scanned masses in the range of 20–700 m/z was used for qualitative determinations of the tested samples. Before the measurements, the samples were extracted in hexane in a ratio of 1:100. The microliter phase dissolved in hexane was taken with a syringe for further analysis. The injection volume of the samples was equal to 1 µL.

6.3. Measurement of Engine Characteristics, Fuel Consumption, and Emissions at Full Engine Load

During the present study, the engine characteristics were determined for the diesel engine used in a Citroen C5 II 1.6 HDI 2008 100 kW operating under full engine load. Such an engine has, nominally, a cubic capacity equal to 1560 cc, maximum power equal to 80 kW at 4000 rpm, and maximum torque equal to 240 Nm at 1750 rpm [41]. The measurement of fuel consumption and emissions were determined for this diesel engine under zero engine load and under full engine load. The way the fuel was supplied to the engine was slightly changed for the time of measurements. Instead of the classic method of supplying fuel from the vehicle's tank to the low-pressure fuel pump, an additional 1 L transparent plastic fuel tank was introduced with a metered amount of fuel connected with the said fuel pump. During measurement, the time and the actual fuel level in the tank were recorded (using a mobile phone camera). The density of fuel was determined in the following manner. Using a graduated glass beaker, the amount V_i of i-th fuel was measured, equal to 50 mL. The beaker of fuel was weighed, and then, after the fuel was withdrawn and the beaker was dried, it was weighed. The difference in the masses measured in this way allowed

estimating the mass m_i of the i-th fuel. The density $\rho_i \left[\frac{g}{cm^3}\right]$ of such a fuel was estimated from Equation (1).

$$\rho_i = \frac{(m_i + m_b) - m_b}{V_i}; i = \begin{cases} 1, \text{ for pure diesel} \\ 2, \text{ for diesel} + 6\% \text{ MEYG}, \\ 3, \text{ for diesel} + 6\% \text{ MEBG} \end{cases} \quad (1)$$

where:

$m_i + m_b$—measured sum of the beaker mass and the i-th fuel mass,
m_b—measured mass of beaker,
m_i—mass of the i-th fuel, while: i = 1 for pure diesel, i = 2 for the blend of diesel and 6% of methyl ester of yellow grease (rapeseed oil), i = 3 for the blend of diesel and 6% of methyl ester of brown grease (goose fat),
V_i—volume of the i-th fuel equal to 50 mL.

It was assumed that during the measurements, the density of the fuel delivered to the engine did not change; in particular, there was no suction of false air with impurities.

The i-th fuel consumption $g_{ei}(n)$ at the engine speed n set was estimated from Equation (1).

$$g_e(n) = \frac{\rho_i \cdot [V_{i0}(n) - V_{ie}(n)]}{P_i(n) \cdot t_i(n)}, \quad (2)$$

where:

$g_{ei}(n)$—the i-th fuel consumption at the engine speed n set,
ρ_i—the i-th fuel density obtained from Equation (1),
$V_{i0}(n)$—the i-th fuel volume registered at the beginning of the measurement process of the i-th fuel consumption at the engine speed n set,
$V_{ie}(n)$—the i-th fuel volume registered at the end of the measurement process of the i-th fuel consumption at the engine speed n set,
$t_i(n)$—time registered for the measurement process of the i-th fuel consumption at the engine speed n set,
$P_i(n)$—measured engine power at the engine speed n set under full engine load, as described further.

6.3.1. Measurement under Full Engine Load

The engine characteristics, including engine power P versus engine speed n and engine torque M versus engine speed n were obtained on the Dynomet Roller Dynamometer [42] for the engine operating under full load at engine speed n sequentially set to the value from the range of 1000–4000 rpm every 500 rpm. The measurements were realized as follows:

- First, the engine operated at idle speed until reaching the temperature value of the balance temperature;
- Then, the additional transparent plastic tank was replaced by the other one with the same dose of the pure diesel;
- Engine characteristics were obtained for the diesel engine supplied with pure diesel (fuel quality and content as delivered);
- Simultaneously for each engine speed value set, the time of engine operation and volume of fuel consumed were determined;
- Additionally, for each engine speed value set, the engine emissions were measured using the Elwico unit [43] comprising an exhaust gas analyzer and an opacimeter;
- Then, the additional tank was replaced with the one filled with diesel with 6% of biodiesel in the form of the methyl ester of rapeseed oil (blend quality and content as delivered);
- Next, the engine characteristics, time of engine operation, volume of fuel consumed, and engine emissions were determined for the same engine speed n values as for the case of pure diesel supply;

- Then, the additional tank was replaced with the one filled with pure diesel;
- The engine was operated once again at idle speed until reaching the temperature value of the balance temperature;
- Next, the additional tank was replaced with the one filled with diesel with 6% of biodiesel in the form of methyl ester of goose fat obtained from the transesterification process described earlier;
- Then, the engine characteristics, time of engine operation, volume of fuel consumed, and engine emissions were determined for the engine speed value n equal to 1500 rpm;
- Next, the engine was supplied with fuel from the vehicle tank and operated once again at idle speed until reaching the temperature value of the balance temperature.

6.3.2. Measurement under Zero Engine Load

The measurement of fuel consumption and emissions of the diesel engine operating under zero engine load was performed in the Diagnostic Station in the Vocational Automotive High School of Lodz in Poland. Figure 1 presents the vehicle in this Diagnostic Station.

Figure 1. Measurement of fuel consumption and emissions of the diesel engine applied in the vehicle Citroen C5 II 1.6 HDI 2008 100 kW in the Diagnostic Station in the Vocational Automotive High School of Lodz in Poland.

The engine speed was coarsely controlled using the engine speed indicator on the dashboard of the vehicle. More accurately, the engine speed was measured using measuring unit Tester XENON 310U WTM with a piezoelectric sonde fastened on one of the high-pressure fuel lines of the engine.

The measurements were realized similarly as for the case of the full engine load. However, for each engine speed value set, the engine emissions were measured using an exhaust gas analyzer Arcon ISC Oliver K9000 and an opacimeter ISC OLIVER D60.

7. Results and Discussion

The obtained results comprised these related to the chromatographic analysis of fuels and engine characteristics determined under full engine load for three fuels studied. The other results related to the fuel consumption end engine emissions determined under both zero and full engine load for the mentioned fuels.

7.1. Results from Chromatographic Analysis of Fuels Supplied to the Combustion Engine

The obtained chromatogram for pure diesel is shown in Figure 2. The highest amount of about 19%, related to 9-octadecenoic acid, methyl ester. Amounts over 5% were observed for eicosane, 2,6-dimethyl-heptadecane, 4-ethyl-tetradecane, hexadecane, pentadecane, tetradecane, and 2,3-dihydro-4,7-dimethyl-1H-indene. The other amounts were below 5%.

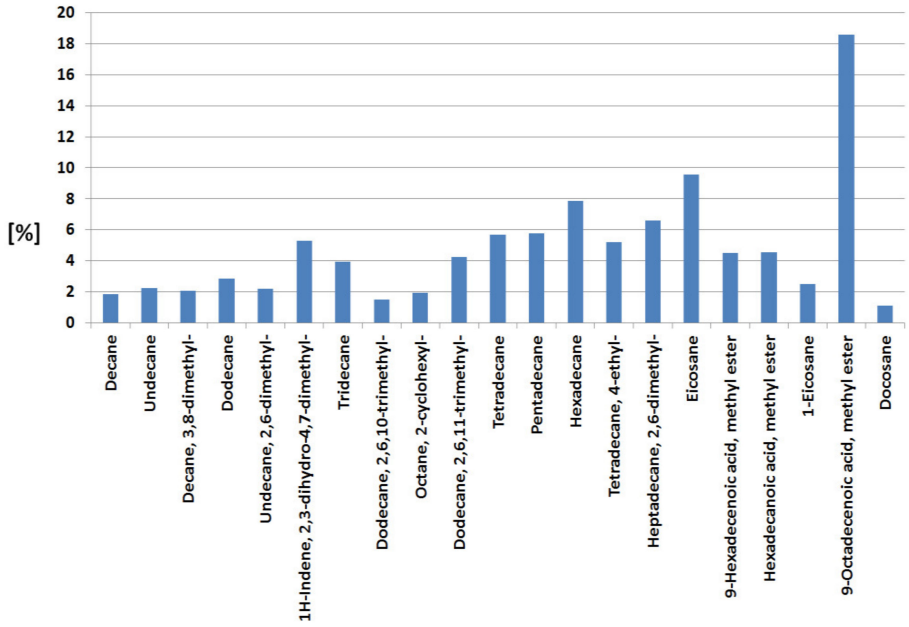

Figure 2. Chemical content of pure diesel supplied to the combustion engine studied.

The obtained chromatogram for diesel with the addition of 6% of methyl ester of yellow grease MEYG (rapeseed oil methyl ester) is presented in Figure 3. The highest amount, about 8%, is related to 2,6-dimethyl-heptadecane. Amounts of over 5% were observed for 3-methyl-dodecane, pentadecane, 4-methyl-tridecane, tetradecane, 2,6,11-trimethyl-dodecane, and 3,8-dimethyl-decane. The other amounts were below 5%.

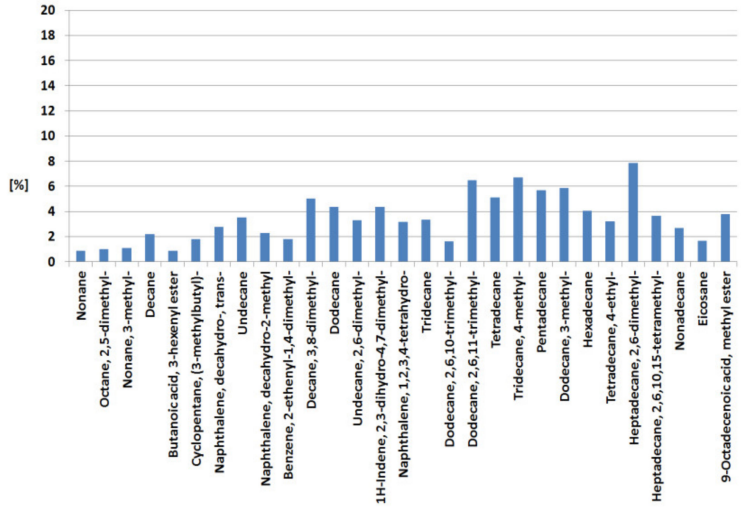

Figure 3. Chemical content of diesel with addition of 6% of methyl ester of yellow grease MEYG (rapeseed oil methyl ester).

The obtained chromatogram for diesel with the addition of 6% of methyl ester of brown grease MEBG (goose fat methyl ester) is presented in Figure 4. The highest amount, about 8%, is related to 9-octadecenoic acid, methyl ester. Amounts of over 5% were observed for eicosane, 2,6-dimethyl-heptadecane, 3-methyl-dodecane, pentadecane, 4-methyl-tridecane, tetradecane, and 2,3-dihyfro-4,7-dimethyl-1H-indene. The other amounts were below 5%. To our knowledge, this is the first report for the blend of diesel and 6% biodiesel in the form of methyl ester of goose fat.

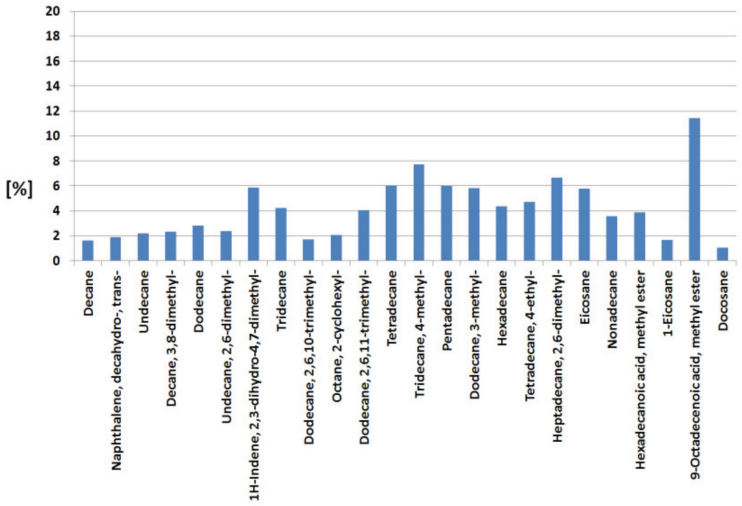

Figure 4. Chemical content of diesel with addition of 6% of methyl ester of brown grease MEBG (goose fat methyl ester).

7.2. Resulted Engine Characteristics

The engine characteristics obtained from research on a dynamometer under the full load of an engine are shown in Figure 5. They comprised engine torque versus engine speed M(n) and engine power versus engine speed obtained for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester. The latter is related to only one characteristic point in the waveform. For pure diesel, the maximum power was lower by about 3% compared to that presented in [44]. The maximum torque was lower by 4.3% compared to that presented in [44]. These decreases probably resulted from the wear of engine components. Under full-load of the engine, the addition of 6% of rapeseed oil methyl ester to the diesel resulted in a weakening of engine power by 8% and engine torque by about 4%. The addition of 6% of goose fat methyl ester to the diesel resulted in an enhancement of engine power by about 1%. It was accompanied by no visible change in the engine torque.

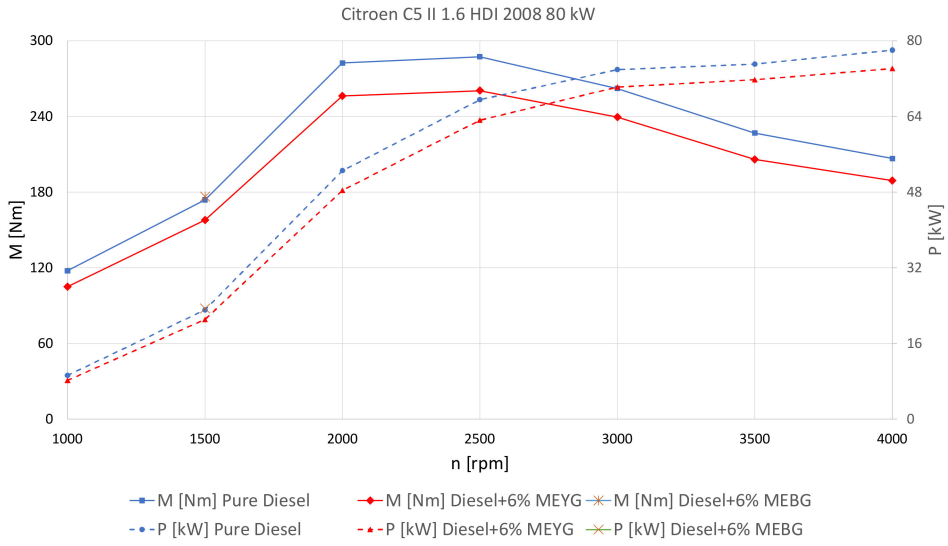

Figure 5. The engine characteristics: Torque M(n) and Power P(n) under full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester and diesel with 6% of goose fat methyl ester.

7.3. Resulted Fuel Consumption and Emissions at Zero Engine Load

The fuel consumption g_e obtained at zero engine load is presented in Table 1. The addition of 6% of rapeseed oil methyl ester into diesel resulted in an increase in fuel consumption by 8.6%. The addition of 6% of goose fat methyl into diesel resulted in an enhancement of 3.4% of such consumption.

Table 1. The fuel consumption g_e at zero engine load.

g_e [g/kWh]		
Pure Diesel	**Diesel + 6% MEYG**	**Diesel + 6% MEBG**
580	630	600

The engine emissions of CO, CO_2, and PM obtained at zero load of engine supplied with pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 6. The emissions of NO_x, O_2, and HC under such conditions are presented in Figure 7. The addition of 6% of rapeseed oil methyl ester to diesel caused a small enhancement of CO and HC emissions and a more clearly visible increase in CO_2 and decrease in PM emissions compared to the engine supplied with pure diesel. The addition of 6% of goose fat methyl ester to diesel resulted in a minor increase in CO emissions and a more clearly visible enhancement of HC and CO_2 emissions, and a decrease in PM emission, in comparison to the case of pure diesel.

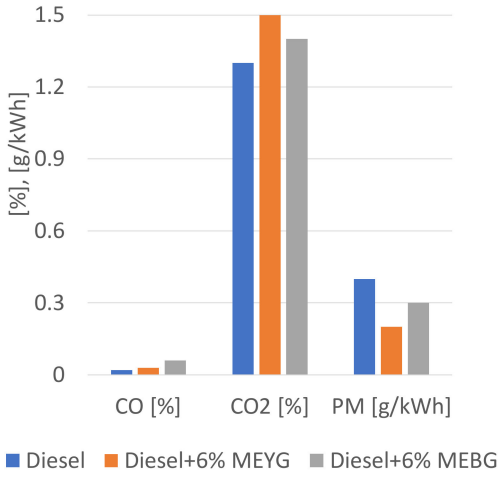

Figure 6. The engine emissions of CO, CO_2, and PM obtained at zero load of engine supplied with pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively.

7.4. Resulted Fuel Consumption and Emissions at Full Engine Load

The fuel consumption g_e versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, is presented in Figure 8. For the pure diesel supply of the engine, the obtained values of fuel consumption were lower by about 15–17% compared to these presented in [30], which were obtained for a four-stroke, common rail fuel system, water-cooled, four-cylinder diesel engine with a cubic capacity equal to 1910 cc, compression ratio of 5.18:1, maximum power equal to 79 kW at 4000 rpm, and maximum torque equal 200 Nm at 1750 rpm. The addition of 6% of rapeseed oil methyl ester to diesel resulted mostly in an increase in fuel consumption. Contrary, the slight resulted decrease in such consumption was observed only for the engine speed equal to 3500 rpm. The addition of 6% of goose fat methyl ester to diesel resulted in a small enhancement of the fuel consumption at engine speed equal to 1500 rpm.

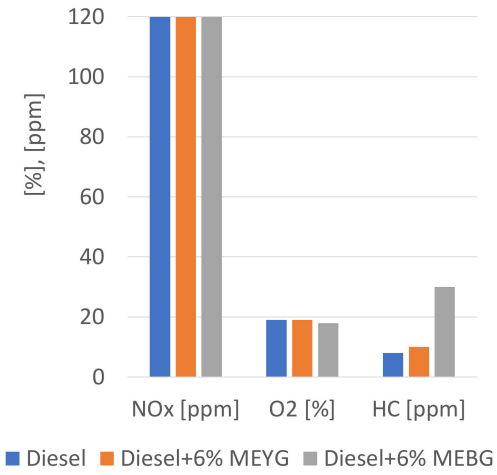

Figure 7. The engine emissions of NO_x, O_2 and HC obtained at zero load of engine supplied with pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively.

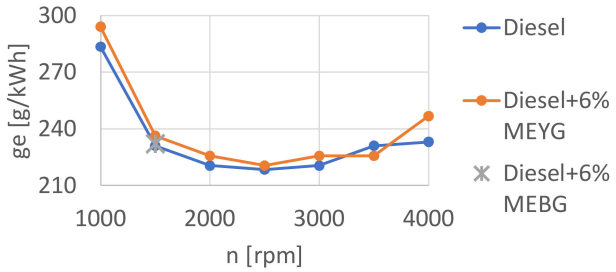

Figure 8. The fuel consumption g_e at full engine load.

The emissions of CO versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 9. The addition of 6% of rapeseed oil methyl ester to diesel resulted in a decrease in CO emissions up to 80%. For comparison, the decrease in CO emissions when the blend of diesel and 5% methyl ester of rapeseed ester was used instead of pure diesel was below 52% for a four-stroke, four-cylinder, water-cooled, direct injection, naturally aspirated diesel engine D-243 with maximum power equal to 59 kW and the splash volume equal to 4.75 L [45]. This decrease weakened with engine speed. The addition of 6% of goose fat methyl ester to diesel resulted in a small enhancement of the CO emissions at engine speed equal to 1500 rpm.

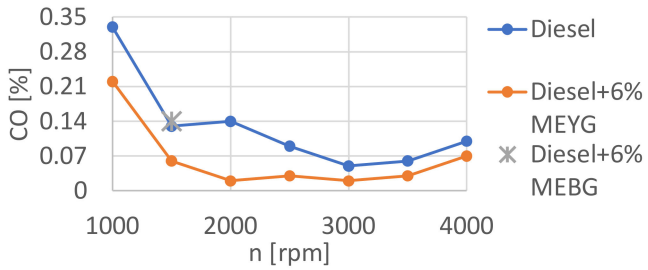

Figure 9. The CO emissions at full engine load.

The emissions of CO_2 obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 10. The addition of 6% of rapeseed oil methyl ester to diesel resulted in

an increase in the CO_2 emissions for engine speed below 2000 rpm and in a decrease in it for engine speed above 2000 rpm. The smallest change occurred at engine speed equal to 2500 rpm. This was contrary to the increase in CO_2 emissions from the engine supplied by the blend of diesel with 20% rapeseed methyl ester by 10% compared to the case of supply with diesel [46]. Such contrary features can be affected by a difference in the mentioned contents of rapeseed methyl ester in the blends with diesel. The addition of 6% of goose fat methyl ester to diesel resulted in a decrease in the CO_2 emissions by 4.5% at engine speed equal to 1500 rpm.

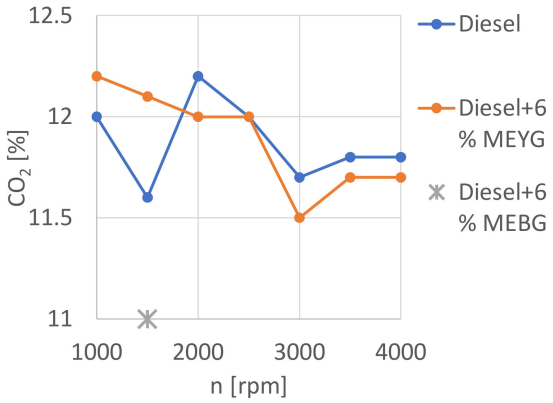

Figure 10. The CO_2 emissions at full engine load.

The emissions of HC versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 11. The addition of 6% of rapeseed oil methyl ester to diesel resulted in an increase in the HC emissions for all engine speeds. The smallest change occurred at engine speed equal to 3000 rpm. For the case of engine supply by pure diesel and by the blend of diesel with 6% of rapeseed oil methyl ester, the HC emissions were at least twice higher than HC emissions from diesel engine supplied with the blend of diesel and neat rapeseed methyl ester for all engine speeds [45]. The higher HC emissions during the present study could result from the significant wear of components of the diesel engine studied. The addition of 6% of goose fat methyl ester to diesel resulted in a triple increase in the HC emissions at engine speed equal to 1500 rpm.

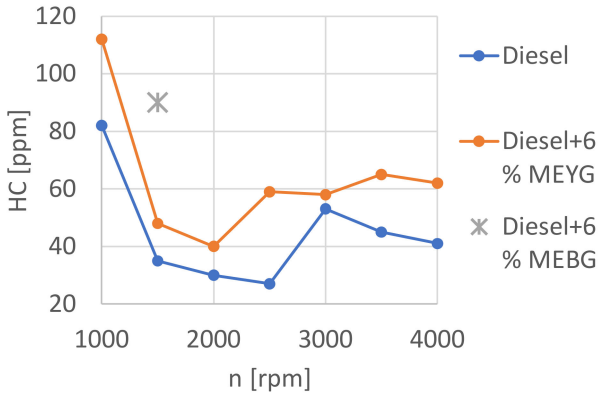

Figure 11. The HC emissions at full engine load.

The emissions of NO_x versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 12. The emission of NOx was lower by 40% compared to that reported for the diesel engine presented in [45]. The addition of 6% of rapeseed oil methyl ester to diesel resulted in an increase in NO_x emissions for all engine speeds. The

smallest change occurred at engine speed equal to 3000 rpm. The addition of 6% of goose fat methyl ester to diesel resulted in an increase in the HC emissions by 31% at engine speed equal to 1500 rpm.

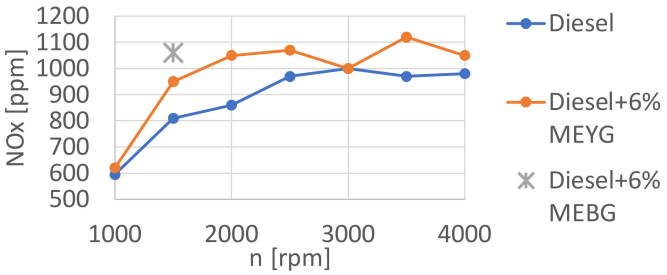

Figure 12. The NO_x emissions at full engine load.

The total emissions of PM versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester and diesel with 6% of goose fat methyl ester, respectively, are shown in Figure 13. The addition of 6% of rapeseed oil methyl ester to diesel resulted in a decrease in the TPM emissions for all engine speeds. The smallest change occurred at engine speed equal to 2000 rpm. The relative decrease in the TPM emissions was over 50%. It was much more compared to the average decrease in PM emissions for the diesel engine supplied with a blend of diesel with 20% of methyl ester of rapeseed oil compared to the engine supplied with pure diesel [47]. Such a difference was affected by a difference in amounts of methyl ester of rapeseed oil in the blends with diesel used to supply the engines. The addition of 6% of goose fat methyl ester to diesel resulted in a decrease in the TPM emissions by 3% at engine speed equal to 1500 rpm.

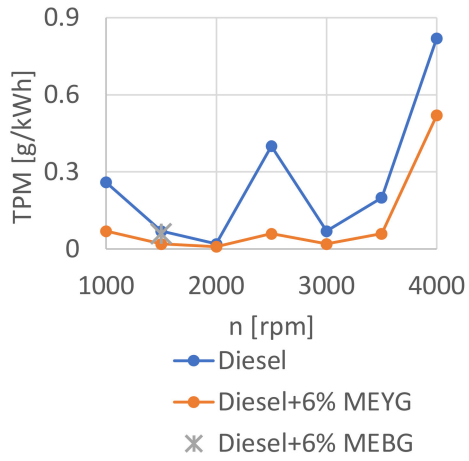

Figure 13. The total emissions of PM at full engine load.

The amount of O_2 in exhaust gas versus engine speed obtained at full engine load for pure diesel, diesel with 6% of rapeseed oil methyl ester, and diesel with 6% of goose fat methyl ester, respectively, is presented in Figure 14. The addition of 6% of rapeseed oil methyl ester to diesel resulted in a decrease in the amount of O_2 in exhaust gas for engine speed above 1500 rpm. Below the latter, it was observed an increase in such an amount. The smallest change occurred at engine speed equal to 2000 rpm. The addition of 6% of goose fat methyl ester to diesel resulted in an increase in the amount of O_2 in exhaust gas by 2.7% at engine speed equal to 1500 rpm.

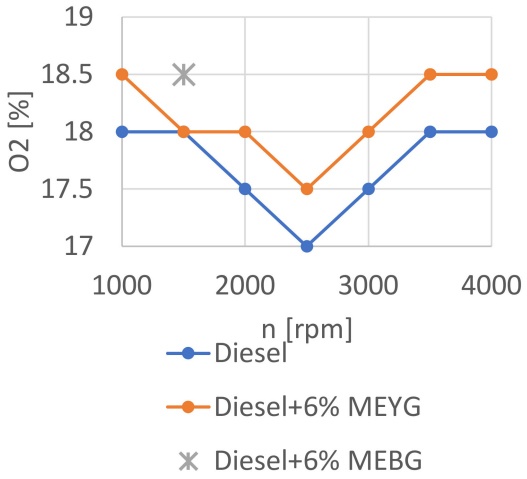

Figure 14. The amount of O_2 in exhaust gas at full engine load.

8. Conclusions

Based on the obtained results, some conclusions were made.

1. The comparison of the effect of the diesel engine supply with three fuels, including pure diesel, a blend of diesel with 6% of methyl ester of rapeseed oil (yellow grease), and one with 6% of methyl ester of goose fat (brown grease) on the engine characteristics, fuel consumption, and engine emissions was performed.
2. Obtained biodiesel containing 6% yellow grease clearly differed not only from pure diesel but also much more from the biodiesel containing 6% brown grease.
3. Under a full load of the engine, the addition of 6% of yellow grease to the diesel allowed a decrease in engine power by 8% and engine torque by about 4%, while the addition of 6% of brown grease to the diesel allowed an increase in engine power about 1% and practically resulted in no change in the engine torque.
4. Under 0% load of the engine, the addition of 6% MEYG to diesel resulted in a minor increase in CO and HC emissions and a more clearly visible increase in CO_2 and decrease in PM emissions compared to the case of pure diesel.
5. Under 0% load of the engine, the addition of 6% MEBG to diesel caused a small enhancement in CO emissions and a more clearly visible increase in HC and CO_2 emissions, and a decrease in PM emissions in comparison to the case of pure diesel.
6. Under full load of the engine, the addition of 6% MEYG to diesel resulted in a clear decrease in CO and PM emissions for all engine speeds and an enhancement in NO_x and HC emissions for all engine speeds, compared to the case of pure diesel. The fuel consumption was a little higher, but rather for the lower engine speed, the CO_2 emission varied with engine speed compared to the case of pure diesel.
7. Under full load of the engine, the addition of 6% MEBG to diesel resulted in a small enhancement in the fuel consumption, a clear increase in NO_x and HC emissions, a small decrease in PM emission and a clear decrease in CO_2 emissions, while CO emissions were not changed compared to the case of pure diesel.

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