Yellow and brown grease—characteristics of compression-ignition engine

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**Abstract.** This paper presents the results of analysis done on a compression-ignition engine supplied with methyl ester of rapeseed oil (Yellow Grease), methyl ester of goose fat (Brown Grease) and pure diesel. The analysis included the engine characteristics, emissions and fuel consumption. Results also include chromatographic analysis for all of the three fuels. Additional evaluation was done on a vehicle idling and under load.

**Keywords:** biodiesel, yellow grease, brown grease, diesel engine, fuel consumption, engine emission

1. **Introduction**

Both insufficient coverages of increasing energy demand and the harmful environmental effects of fossil fuels made biofuels both solid ones [1,2] and liquid ones [3] an interesting alternative to them. Liquid biofuels, particularly derived from inedible biomass are promising renewable energy sources for transport. It is due to they are usable within current infrastructures and also need less 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 and need further studies on methods decreasing their level of harmfulness [3].

Nowadays the demand to replace the commonly utilized diesel by alternative fuels, particularly the bioderived ones, has become more and more visible [4,5].

It is necessary to notice that there are some differences between biodiesels and renewable bio-diesels, both being alternative to the fossil diesel sometimes also called petrodiesel [6-8].

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 the a minimum volume of renewable fuels contained in transportation fuel [9]. 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 [6]. According to [10] biodiesel is often blended with petroleum diesel in ratio range from 5% to 20% biodiesel, or B5-B20. The Renewable Fuel Standard (RFS), a federal program that mandates the blending of biofuels into the nation’s fuel supply generally encouraged higher biodiesel blends.

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 hydro-thermal processing [11].
The 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 [12]. Van Gerpen [13] stated that biodiesel is the form of biofuel obtained from vegetable oils and animal fats and is an important alternative to fossil diesel. It is renewable, non-toxic, biodegradable, sulfur, and benzene-free, can be applied in various diesel engines without any modification, and can be blended with fossil diesel at any given ratio [14-19].

Diaz-Felix et al. [20] stated that biodiesel is a renewable fuel comprised of fatty acid methyl esters (FAMEs). However, biodiesel exhibited lower oxidative stability and cold flow properties, higher viscosity and density, and higher NOx emissions in comparison to fossil diesel [21-24]. Additionally, bio-diesel is characterized by higher production costs compared to fossil diesel [25-27]. Some activities, including the use of the cheaper technologies, are carried out to decrease such costs [28-34].

Huang et al. [35] reviewed various types of biodiesel, the characteristics, processing, and eco-nomics of industry related to biodiesel. They discussed particularly the application of biodiesel in the automobile industry.

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

2. Feedstocks for Biodiesel

According to [36] there are six EPA-approved biodiesel and renewable diesel production feed-stocks are soybean oil, yellow grease, distillers corn oil, animal fats, canola oil and camelina. As of September 2017, their respective content the biomass-based diesel market were approximately 46%, 15%, 15%, 13%, 11% and below 1%.

Bartha-Vári et al. [37] noted that biodiesel can be produced from edible oils including soybean and palm oil, and also non-edible ones like cooking oils and algal or fungal oils.

Edible oils are cheaper for biodiesel production in comparison to the algal oils [38]. 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 be also produced from the fatty phase of wastes (brown grease – BG) or palm fatty acid distillate (PFAD) [39].

The mentioned raw materials contain a high concentration of free fatty acids (FFAs). Due to their high content of the OA and LA, and palmitic acid in PFAD, such acids are used as model systems during investigations [40-42].

According to Gebremariam and Marchetti [43] fresh vegetable oils are used for biodiesel pro-duction at an industrial scale. However, Mansir et al. [44] stated that most biodiesel production costs resulted from utilizing fresh edible oils as feedstock.

Therefore, alternative, 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 [45-51].

Elgharbawy et al. [52] noticed that feedstocks of biodiesel varies between edible oil such as the oil of sunflower, soybean and coconut or non-edible oil such as the oil of Jatropha, jojoba and used cooking oil.

However, the high free fatty acid (FFA) content of mentioned feedstocks resulted in saponification and emulsification in the presence of homogeneous base catalysts, limiting biodiesel yield and making its separation from glycerol difficult [53,54].

According to [55] biodiesel is found as a nontoxic, biodegradable and renewable alternative fuel applicable with little or no engine modifications. Biodiesel can be produced from low cost oils (restaurant waste, frying oils, animal fats) comprising high levels of free fatty acids.
Grzelak and Zoltowski [56] proposed the use of waste oils to produce hydrogenated vegetable oils (HVOs) and described the 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 method of biodiesel production at an industrial scale is the alkali-catalyzed transesterification of the aforementioned fresh vegetable oils [43]. According to Elgharbawy et al. [52] biodiesel is often obtained from vegetable oil via transesterification reaction substituting the organic group (alkyl) of an alcohol by the organic group of a triglyceride producing FAME and glycerol. The authors reviewed four types of the transesterification processes, acid-catalyzed transesterification, alkaline catalyzed transesterification, enzyme catalyzed transesterification and non catalyzed supercritical methanol. They noticed that the alkaline catalyzed transesterification method is the most commonly utilized process due to the fastest reaction, the highest yield, the mildest reaction condition, the lowest cost, corrosive, and toxicity.

As reported in [57,58] biodiesel can be produced via transesterification and esterification. The transesterification resulted in formation of alkyl esters of FFAs and glycerol as a byproduct of the reaction between mono-, di- or triglycerides and alcohol. During the esterification, a reaction between alcohol and FFA takes place resulting in formation of alkyl esters. Both esterification and transesterification belong to the group of equilibrium reactions [59]. As methanol and ethanol are used in such reactions [57], therefore both methyl and ethyl esters are found to be biodiesels [60]. The activation of transesterification and esterification reactions is realized by agitation and heating [61].

Ultrasonication can also be applied for activation of chemical reactions, as the esterification of FFAs under ultrasonic activation proceeds quickly and efficiently, without additional heating [62-64]. However, application of ultrasonication is expensive. Furthermore, unwanted direct contact between the treated corrosive media and ultrasonic devices is possible, which can be prevented by a decrease of the residence time of reagents in the ultrasonic reactor or by the use of contactless reactors [62]. Activation of reactions also needs a chemical or enzymatic catalyst [61]. Chemical catalysts can basic or acid. Basic catalysts are better than the latter, as allow reaction at relatively low temperatures (60–90 °C) and pressures (1.5–4 atm). However they are highly sensitivity to water and reactive with FFAs in saponification [65].

The acid catalysis are preferred [66] but have longer duration (over 12 h), need higher temperatures (120–250 °C) and a larger amount of catalyst (here of acid type) compared to the basic catalysis. The sulfuric acid insensitive to small amounts of water, it is usually applied as a catalyst in the esterification of FFAs [65].

As homogeneous aggressive catalysts cause corrosion of equipment they can be replaced by heterogeneous basic or acidic catalysts [39]. The wide application of solid-phase catalysts is limited by problems in mass transfer, resolvable using an oscillatory flow technique, microwave irradiation or ultrasonic technology [67]. Lewis acids can also be utilized as catalysts in biodiesel production [68-70]. Lewis acids are effective catalysts for both esterification and transesterification reactions [71,72], and in both homogeneous and heterogeneous forms [73]. Lewis acid boron trifluoride in methanol was proposed as a good catalyst for the esterification of fatty acids [74].

Heterogeneous catalysis by Lewis acids such as AlCl3, AlF3 and ZnCl2 was found effective in transesterification of canola oil for biodiesel production [75-77]. Various tin-based catalysts (Sn(II) acetate, Sn(II) chloride and Sn(II) 2-ethyl-hexanoate) exhibited high catalytic activity in esterification and transesterification of vegetable oils [78].
The use of Lewis acid catalysts allows proceeding the reaction under not harsh conditions, ambient temperature and in a short time [79].

A two-step biodiesel production process from waste cooking oil through recycling crude glycerol esterification catalyzed by alkali catalyst was described in [80].

The homogeneous base catalysts such as potassium hydroxide, sodium hydroxide, sodium methoxide, and potassium methoxide often utilized for transesterification are corrosive, difficult to be recycled, and are removed from the reaction mixture by water washing, causing enhanced amounts of wastewater [81-84]. According to Alaei et al. [85] biodiesel obtained using homogenous base catalysts can be contaminated with metal ions.

4. Research on Biodiesel from Yellow Grease

Several studies were conducted on biodiesels obtained from various Yellow Greases.

Panchal et al. [86] 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 CH3O2S 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 of 94%. The biodiesel properties tested, such as kinematic viscosity at temperature equal to 408 °C, specific gravity at 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. [87] investigated the transesterification reaction of Pongamia pinnata oil also known as Karanja oil in supercritical methanol in one-step catalyst-free process. Triglyceride (TG) conversion and the yield of FAMEs at an alcohol-to-oil molar ratio of 43:1 were investigated in the temperature range of 250-350 °C under pressure 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 conditions. The optimal conditions for such a reaction related to temperature of 300 °C and reaction time of 90 min allowing almost complete triglyceride conversion. Then, the high level of thermal decomposition occurred from 325 °C, mainly due to the degradation of polyunsaturated fatty acid methyl esters. Maximum degree of thermal decomposition of 38% took place at 350 °C in the end of reaction time.

Goembira and Saka [88] studied biodiesel production from Pongamia pinnata oil using an interesterification process called one-step supercritical methyl acetate method for under reaction condition 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 mentioned reaction condition. It was 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 were in agreement with biodiesel standards.

Özçelik et al. [89] 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 its 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 [90] conducted synthesis of glycerol free-methyl esters (FAME) for the transesterification of Jatropha oil utilizing dimethyl carbonate (DMC) as 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%.

Canakci and Van Gerpen [55] studied the effect of the biodiesel produced from high free fatty acid feedstocks on engine performance and emissions. One biodiesel was prepared from animal fat-based yellow grease with 9% free fatty acids. The neat biofuel and its 20% blend with No. 2 diesel fuel were investigated at steady-state engine operating conditions in a four-cylinder turbocharged diesel engine. Biodiesel fuel allowed obtaining limited emissions of PMs, CO, and unburned HC. However,
the NO\textsubscript{x} emission were enhanced by 11\% for the yellow grease methyl ester. The conversion of the biodiesel fuel energy to work was close to that of diesel fuel. According to [20], the esterification reduced the FFA levels in Yellow Grease, but large amounts of methanol had to be employed to drive the reaction to high yield. The authors investigated the effect of FFA in the range of 2\% to 32\% (w/w) at three different molar ratios of methanol to FFA (4.5: 1, 9: 1, 18: 1), fiding the non-linear nature of the effect.

Gaurav et al. [91] suggested the use of the catalytic distillation (CD) combining a catalytic reaction and separation via distillation in the same distillation column for the biodiesel production from yellow grease containing both triglyceride and free fatty acid. They emphasized an advantage of CD in comparison to a conventional biodiesel processes due to the limited number of distillation columns, waste streams and greenhouse gas emissions.

Duda et al. [92] 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\% share (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 speed of 1500 rpm and mid-load range from 100 Nm to 200 Nm. They found that the addition of the mentioned renewable component to a fuel blend positively affected performance parameters and weakened engine emissions, in the majority of cases.

5. Research on Biodiesel from Brown Grease

Less studies were conducted on biodiesel obtained from various Brown Greases. According to [93], since 3 December 2021 the International Sustainability and Carbon Certification (ISCC) has 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". Such a definition has excluded waste edible oil collected from sewers from being classed as brown grease. Oil removed from sewers was instead covered under the sewage sludge category expanded to include fats, oils and grease (FOG) from the sewage system, while the separate sewage system FOG category has been deleted.

Kolet et al. [94] stated that brown grease is a mixture of oils, fats, solids and detergents from food industry wastes that is captured in grease traps. Brown grease contains oils and fats convertible into biodiesel. However, the high concentration of free fatty acids in brown grease excluded 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\textsubscript{3} and AlCl\textsubscript{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.

The researches from the same group also in [39] combined the application of Lewis catalysts with ultrasound activation to the scheme of biodiesel production from FFAs.

Tran et al. [95] reviewed recent achievements in the production of biodiesel from grease trap waste (GTW).

According to Hums et al. [96] a 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 relatively 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 25ppm – 50ppm 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. [97] studied a potential biodiesel feedstock in form of larval grease extracted from yellow mealworm beetle (Tenebrio molitor L.) (YMB), a post-harvest scavenger, fed with decayed vegetables in 9 weeks before extraction of its grease. Interestingly, 34.2 g biodiesel was got from 234.8 g 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/m³), flash point (127 °C), cetane number (58), water content (300 mg/kg), and methanol content (0.2%).

Spiller et al. [98] 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. It was obtained a yield of 0.55 butyric acid/g sugars confirming also 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. [99] converted brown grease to biodiesel FAME. It was made 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 two-stage reaction prevented the lipase from deactivation. The latter was induced by excess amounts of methanol. They have obtained contents of FAME above 95 wt.% even after 15 cycle reactions.

The research group Duda et al. [92] studied also the performance and emission characteristics of a mentioned earlier diesel engine supplied also 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 weakened engine emissions, in the majority of cases studied.

6. Materials and methods

During present study three kinds of fuel were utilized including:
- pure diesel fuel (as delivered),
- the blend of diesel with 6% of biodiesel obtained from yellow grease, more specifically in the form of methyl ester of rapeseed oil (as delivered),
- the 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 of the vehicle chosen. Such a vehicle was investigated on its fuel consumption and emissions under both zero and full load of the engine.

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 250ml,
- reflux cooler,
- magnetic stirrer,
- water bath,
- thermometer,
- manifold with a capacity of 250ml,
- measuring cylinder,
• beakers,
• conical flask with a stopper,
• glass funnel.

6.1.2. Methodology

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

Next, for a rounded flask with a capacity of 250 ml were introduced with 120 g of goose lard, a magnetic rod and the flask was fitted with a reflux condenser. The whole 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 minutes. The reaction blend was then transferred to a separating funnel, 50 ml of 10% HCl was added, mixed and allowed to separate (about 10-20 minutes). The lower water-glycerin layer was separated and the upper oily layer was washed twice with distilled water (2 x 50 mL). Washing was done carefully by slightly tilting the funnel to avoid the formation of stable emulsions.

The procedure was repeated to obtain amount of biodiesel needed for mixing with pure diesel to obtain the estimated amount of fuel necessary to supply the diesel engine during investigation. To be more specific, that 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 at its full load. So 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 (30m, 0.250mm) 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 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 applied in the vehicle Citroen C5 II 1.6 HDI 2008 100 kW operating under full engine load. Such an engine had 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 [100]. 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 was recorded (using a camera of the mobile phone). 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. That beaker with fuel was weighed, and then, after the fuel was withdrawn and 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 $d_i$ of such a fuel was estimated from Equation 1.
\[ d_i = \frac{(m_i + m_b) - m_b}{V_i} \]; \( i = \begin{cases} 1, & \text{for pure diesel} \\ 2, & \text{for diesel + 6\% MEYG} \\ 3, & \text{for diesel + 6\% MEBG} \end{cases} \)

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 (2).

\[ g_e(n) = \frac{d_i[V_{io}(n) - V_{ie}(n)]}{P_i(n)t_i(n)} \]  

where:
- \( g_{ei}(n) \) – the \( i \)-th fuel consumption at the engine speed \( n \) set,
- \( d_i \) – the \( i \)-th fuel density obtained from Equation (1),
- \( V_{io}(n) \) – the \( i \)-th fuel volume registered in 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 in the end of the measurement process of the \( i \)-th fuel consumption at the engine speed \( n \) set,
- \( t_i(n) \) – time period 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 Dynomot Roller Dynamometer [101] 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 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 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 [102] 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;
• Engine 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 diesel engine operating under zero engine load was done in the Diagnostic Station in the Vocational Automotive High School of Lodz in Poland. Figure 1 presents such a vehicle in this Diagnostic Station.

![Figure 1. Measurement of fuel consumption and emissions of 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.](image)

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 piezoelectric sonde fastened on one of the high pressure fuel lines of 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 chromatographic analysis of fuels, and engine characteristics determined under full engine load for three fuels studied. The other results related to the fuel consumption and 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 was shown in Figure 2. The highest amount of about 19% related to 9-octadecenoic acid, methyl ester. The 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%.
The obtained chromatogram for diesel with addition of 6% of methyl ester of Yellow Grease MEYG (rapeseed oil methyl ester) was presented in Figure 3. The highest amount of about 8% related to 2,6-dimethyl-heptadecane. The 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%.

The obtained chromatogram for diesel with addition of 6% of methyl ester of Brown Grease MEBG (goose fat methyl ester) was presented in Figure 4. The highest amount of about 8% related to 9-octadecenoic acid, methyl ester. The amounts of over 5% were observed for eicosane, 2,6-dimethyl-heptadecane, 3-methyl-dodecane, pentadecane, 4-methyl-tridecane, tetradecane, and 2,3-dihydro-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 2. Chemical content of pure diesel supplied to the combustion engine studied.](image1)

![Figure 3. Chemical content of diesel with addition of 6% of methyl ester of Yellow Grease MEYG (rapeseed oil methyl ester).](image2)
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 dynamometer under full load of an engine were 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 by only one characteristic point in the waveform. For the pure diesel the maximum power was lower by about 3% compared to that presented in [103]. The maximum torque was lower by 4.3 % compared to that presented in [103]. These decreases were probably resulted from the wear of engine components. Under full load of engine the addition of 6% of rapeseed oil methyl ester to the diesel resulted in weakening of engine power by 8% and engine torque about 4%. Addition of 6% of goose fat methyl ester to the diesel resulted in an enhancement of an engine power about 1%. It was accompanied by no visible change of 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 was presented in Table 1. Addition of 6% of rapeseed oil methyl ester into diesel resulted in an increase of the fuel consumption by 8.6%. Addition of 6% of goose fat methyl into diesel resulted in an enhancement by 3.4% of such a consumption.

| $g_e$ [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 were shown in Figure 6. The emissions of NO$_x$, O$_2$, and HC under such conditions were 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 of CO$_2$ and decrease of PM emissions, compared to the engine supplied with a pure diesel. The addition of 6% of goose fat methyl ester to diesel resulted in a small increase of CO emissions and a more clearly visible enhancement of HC and CO$_2$ emissions, and a decrease of 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.

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.

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, was presented in Figure 8. For the pure diesel supply of engine, the obtained values of fuel consumption were lower by about 15%-17% compared to these presented in [89], which were obtained for four-stroke, common-rail fuel system, water-cooled, four-cylinder diesel engine with 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 of the fuel consumption. Contrary, the slight resulted decrease in such a 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.

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, was shown in Figure 9. The addition of 6% of rapeseed oil methyl ester to diesel resulted in a decrease of CO emission up to 80%. For the comparison, the decrease of CO emission when the blend of diesel and 5% methyl ester of rapeseed ester was used instead 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 [104]. 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.

The emissions of CO 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, was shown in Figure 10. The addition of 6% of rapeseed oil methyl ester to diesel resulted in an increase of the CO emissions for engine speed below 2000 rpm and in a decrease of it for engine speed above 2000 rpm. The smallest change has occurred at engine speed equal to 2500 rpm. It was contrary to the increase of CO emission from engine supplied by blend of diesel with 20% rapeseed methyl ester by 10% compared to the case of supply with diesel [105]. Such contrary feature 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 of the CO₂ emissions by a 4.5% at engine speed equal to 1500 rpm.

![Figure 10. The CO₂ emissions at full engine load.](image)

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, was shown in Figure 11. The addition of 6% of rapeseed oil methyl ester to diesel resulted in an increase of the HC emissions for all engine speeds. The smallest change has 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 emission were at least twice higher than HC emission from diesel engine supplied with the blend of diesel and neat rapeseed methyl ester for all engine speeds [104]. The higher HC emission during present study could result from the significant wear of components of diesel engine studied. The addition of 6% of goose fat methyl ester to diesel resulted in a triple increase of the HC emissions at engine speed equal to 1500 rpm.
The emissions of NO\textsubscript{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, was shown in Figure 12. The emission of NO\textsubscript{x} was lower by 40\% compared to that reported for the diesel engine presented in [104]. The addition of 6\% of rapeseed oil methyl ester to diesel resulted in an increase of the NO\textsubscript{x} emissions for all engine speeds. The smallest change has occurred at engine speed equal to 3000 rpm. The addition of 6\% of goose fat methyl ester to diesel resulted in an increase of the HC emissions by 31\% at engine speed equal to 1500 rpm.

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, was shown in Figure 13. The addition of 6\% of rapeseed oil methyl ester to diesel resulted in an decrease of the TPM emissions for all engine speeds. The smallest change by has occurred at engine speed equal to 2000 rpm. The relative decrease of the TPM emissions were over 50\%. It was much more compared to the average decrease of PM emissions for diesel engine supplied with a blend of diesel with 20\% of methyl ester of rapeseed oil compared to the engine supply with pure diesel [106]. Such a difference was affected by a difference in amounts of methyl ester of rapeseed oil in the blends with diesel used to
supply of engines. The addition of 6% of goose fat methyl ester to diesel resulted in a decrease of 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, was presented in Figure 14. The addition of 6% of rapeseed oil methyl ester to diesel resulted in a decrease of the amount of O$_2$ in exhaust gas for engine speed above 1500 rpm. Below the latter it was observed an increase of such an amount. The smallest change has occurred at engine speed equal to 2000 rpm. The addition of 6% of goose fat methyl ester to diesel resulted in an increase of 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 conclusion was made.

1. The comparison of the effect of the diesel engine supply with three fuels including pure diesel, the blend of diesel with 6% of methyl ester of rapeseed oil (Yellow Grease), and the one with 6% of methyl ester of goose fat (Brown Grease) on the engine characteristics, fuel consumption and engine emissions has been done.

2. Obtained biodiesel containing 6% of Yellow Grease clearly differed not only from pure diesel but also much more from the biodiesel containing 6% of Brown Grease;

3. Under full load of engine the addition of 6% of Yellow Grease to the diesel allowed decreasing of engine power by 8% and engine torque about 4%, while addition of 6% of Brown Grease to the diesel allowed increasing of engine power about 1% and practically resulted in no change of the engine torque;

4. Under 0% load of engine the addition of 6% MEYG to diesel resulted in a small increase of CO and HC emissions and a more clearly visible increase of CO$_2$ and decrease of PM emissions, compared to the case of pure diesel;

5. Under 0% load of engine the addition of 6% MEBG to diesel caused a small enhancement of CO emissions and a more clearly visible increase of HC and CO$_2$ emissions, and a decrease of PM emission, in comparison to the case of pure diesel;

6. Under full load of engine the addition of 6% MEYG to diesel resulted in a clear decrease of CO and PM emissions for all engine speed and an enhancement of NO$_x$ and HC emissions for all engine speed, 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 engine the addition of 6% MEBG to diesel resulted in a small enhancement of the fuel consumption, a clear increase of NO$_x$ and HC emissions, a small decrease of PM emission and a clear decrease of CO$_2$ emission, while CO emission was not changed, compared to the case of pure diesel.

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