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Article

Evaluation of Particulate Matter (PM) Emissions from Combustion of Selected Types of Rapeseed Biofuels

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Abstract: The manuscript describes the results of an experimental study of the level of PM (particulate matter) emissions arising from the combustion of two selected types of biomass (i.e., rapeseed straw pellets and engine biofuel (biodiesel, FAME)), which were derived from rapeseed. The PM emissions from the combustion of biofuels were compared with those obtained from the combustion of their traditional counterparts (i.e., wood pellets and diesel fuel). Both types of pellets were burned in a 10 kW boiler designed to burn these types of fuels. The engine fuels tested were burned in a John Deere 4045TF285JD engine mounted on a dynamometer bench in an engine dyno, under various speed and load conditions. A Testo 380 analyzer was used to measure the PM emission levels in boiler tests, while an MPM4 particle emission meter was used in the engine tests. The combustion (under rated conditions) of rapeseed straw pellets resulted in a significant increase in PM emissions compared to the combustion of wood pellets. The PM emissions during the combustion of wood pellets were 15.45 mg·kg^{-1}, during the combustion of rapeseed straw pellets, they were 336 mg·kg^{-1}, and the calculated emission factors were 44.5 mg·MJ^{-1} and 1589 mg·MJ^{-1}, respectively. In the engine tests, however, significantly lower particulate emissions were obtained for the evaluated biofuel compared to its conventional counterpart. The combustion of rapeseed oil methyl esters resulted in a 40–60% reduction in PM content in the exhaust gas on average for the realized engine speeds over the full load range compared to the combustion of diesel fuel.

Keywords: particulate matter (PM); rapeseed straw pellets; biodiesel; combustion; PM emission levels; pellet boiler; diesel engine; engine dynamometer

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1. Introduction

A closed-loop economy is related to the need to maintain the high value and quality of resources, products, and materials for as long as possible, and to minimize the amount of waste produced by managing it efficiently. A common element in all activities is the effort to close the circulation of materials in the economy [1]. A significant direction of the use of agricultural raw materials in addition to the production of liquid biofuels or the biocomponents of motor fuels is their use in the energy sector. An important role is played by solid biofuels, which are mostly residues from the agricultural and forestry industries, which are components of solid energy fuels or are fuels in their own right. Problems related to these types of energy raw materials not only include their qualitative assessment, but also the impact of their use on the environment [2,3].

Rapeseed straw, which is a waste product in the production of rapeseed oil and biodiesel, can be a valuable energy feedstock with a high calorific value [4–6]. Undeveloped rapeseed straw can also be used in the pressure agglomeration of biomass during the production of compact solid biofuels [7]. Rapeseed straw pellets can be an alternative to wood pellets used in low-power automatically supplied boilers. Such activities are in line with the main objectives of the EU Common Agricultural Policy, in relation to practices that promote environmental and climate protection [8].

In urban conditions, biomass combustion is a major source of particulate matter during the winter seasons, accounting for up to 30% of PM10 [7]. Particulate matter contributes significantly to the total emissions of atmospheric air pollutants accompanying fuel combustion in low-power boilers. The results of studies of the fractional composition of dust emitted from domestic furnaces indicate a significant contribution, depending on the type of furnace and its mode of use, of fine fractions of particulate matter including PM10. Emissions from biomass combustion in domestic furnaces involve an unaccounted-for share of TSP (total suspended particulate) dust emissions [9]. Small domestic boilers and stoves remain the main emitters of PM in many countries, especially during the winter season. In the EU, more than 40% of the energy produced from solid biomass comes from combustion in domestic boilers and stoves [9]. Depending on the local fuel availability, domestic boilers are fueled by wood, biomass pellets, or coal of various types and qualities. During the heating season, in some EU countries, the share of total PM (particulate matter) emissions emitted from biomass combustion in domestic appliances can exceed 80% [10]. Residential biomass combustion is one of the largest sources of fine particles in the global troposphere, which has serious impacts on the air quality, climate, and human health. Because of this correlation and the increasing use of biomass for energy purposes through combustion, emissions from biomass combustion, particularly PM, require further study [8]. It is difficult to obtain quantitative estimates of the contribution of this source to airborne particulate levels because the emission factors vary widely depending on the type of wood, combustion equipment, and operating conditions [10]. There are two main sources of particulate matter emitted from domestic and small district heating boilers: (1) particles formed by incomplete combustion (soot, condensable organic particles—tars) and char; and (2) particles from the inorganic material in the fuel-ash [11].

The analysis of literature reports on the mechanisms of the formation of solid particles in the process of biomass combustion proves that PM emissions depend on the combustion technology, especially on the physical and chemical properties of the biomass being burned [9]. Solid particles are formed mainly from evaporating inorganic components such as KCl, which in the presence of SO_2 undergo further chemical transformations (e.g., to $K_2SO_{4)}$. The composition of the emitted inorganic submicron solid particles mainly includes potassium, chlorine, sulfur, and oxygen, and the process of releasing alkali metals during biomass combustion depends on the mutual ratio of the content of chlorine and alkali metals as well as the presence of sulfur and nitrogen in the fuel [11,12].

Another way to use biomass for energy purposes is the use of biofuels in transportation. Biodiesel (FAME) is produced by a transesterification reaction with methanol, resulting in a mixture of fatty acid methyl esters [13,14].

Particulate matter is also formed during the operation of internal combustion engines, mainly from diesel engines, which can be fueled with biodiesel or fuel containing biodiesel in the form of a biocomponent.

They contain the following components (Figure 1) [15,16]:

- *Insoluble Organic Fraction* (IOF—a part of INSOL), in other words, carbon in the form of soot and products of incomplete combustion of fuel and oil additives;
- *Insoluble inorganic fraction* (INSINOF—a part of INSOL), which consists of ashes, sulfates, trace elements such as iron, phosphorus, calcium, chromium, etc., and mechanical impurities from the environment;
- *Soluble Organic Fraction* (SOF), organic substances absorbed on soot particles (mainly hydrocarbons formed from the incomplete combustion of fuel PM_{FUEL} and oil PM_{LUBE});
- *Soluble Inorganic Fraction* (SINOF), resulting mainly from the presence of sulfur in the fuel, from which sulfuric acid is formed following combustion and because of the presence of water vapor;

- *Soluble Organic Fraction* (SOF), which consists mainly of unburned hydrocarbons resulting from local oxygen deficiency or excess from flame extinction near the cooler cylinder walls or from a drop in charge temperature during expansion.

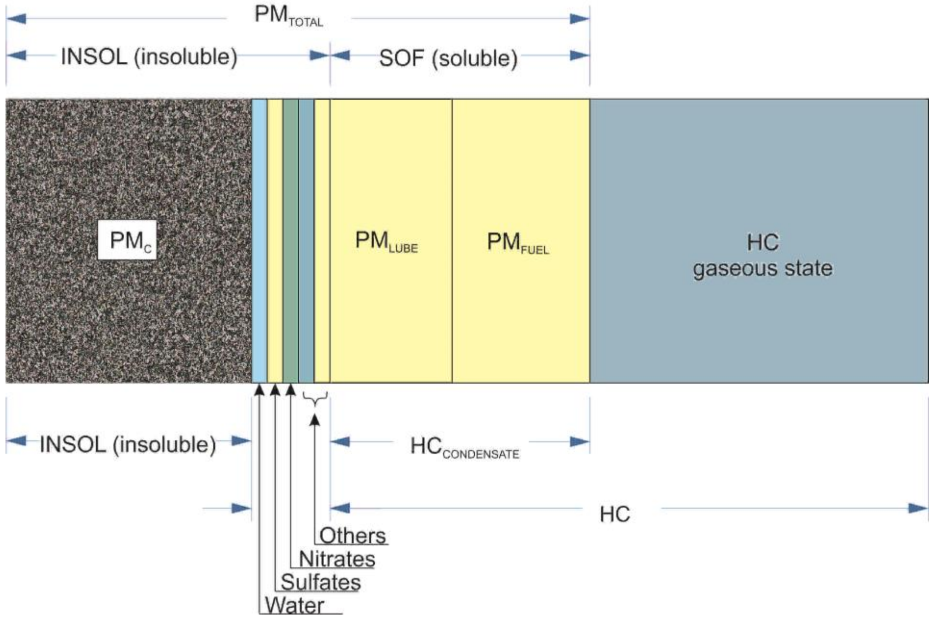

Figure 1. Diagram of the structure of a solid particle.

Typically, diesel engine exhaust contains small (10–80 μm), single elementary particles of soot in the shape of a sphere called nanoparticles and large (10–50 μm) forming clusters of these particles in the form of soot agglomerates or aggregates (more than 100 μm) [15].

The consequence of air pollution is a reduced life expectancy. Particulate emissions are one of the main causes of smog. Particulate matter (PM) air pollution leads to premature deaths from heart disease, stroke, and cancer, and causes acute respiratory infections [17–19]. Air pollution is estimated to cause seven million deaths worldwide each year [20]. In Europe, air pollution is the biggest environmental threat to human health, a leading cause of premature births, deaths, and many diseases [21,22]. Particulate matter PM10 and PM2.5 (particulate matter less than 10 μm and 2.5 μm in size, respectively) are considered especially hazardous to human health, causing respiratory diseases (such as asthma) and even death [23].

The literature data on the emissions and mechanisms of particulate matter from various biofuels are quite scattered, and further work in this area is needed to study, describe, and organize them. In the absence of reports comprehensively treating the effect of using solid and liquid rapeseed biofuels on particulate emissions, it was decided to study them and compare them with fuels considered conventional. The purpose of the study was to analyze the level of PM emissions produced when burning, in different power equipment and varying operating conditions, different types of biofuels made from rapeseed. The biofuels studied were biodiesel (FAME—rapeseed oil methyl esters) used to power compression-ignition engines, and pellets made from rapeseed straw, which is a by-product of edible oil production that can be used for energy purposes. In addition, the obtained test results were compared with those of particulate emissions during the combustion of conventional diesel fuel and wood pellets as the primary fuel for an automatic low-power pellet boiler. This comprehensive approach to the energy use of biofuels obtained on the basis of rapeseed in comparison with their conventional counterparts is a continuation of emissivity studies, the results of which in relation to selected greenhouse gases were presented in [6].

2. Materials and Methods

2.1. Boiler Tests

Two types of solid biofuels were used in the boiler emission tests. Rapeseed straw pellets were produced for the study, and commercial wood pellets of ENplus A1 quality grade were obtained from coniferous trees. In both cases, the pellets were 6 mm in diameter. To characterize the pellets, proximate and ultimate analyses were performed and LHV and HHV were determined. The results are shown in Table 1.

Table 1. Chosen characteristics of the tested pellets.

Parameter	Wood Pellets	Rape Straw Pellets
Carbon (%)	49.5	40.1
Hydrogen (%)	6.06	5.8
Nitrogen (%)	0.17	0.8
Sulfur (%)	0.02	0.31
Oxygen (%) *	38.25	33.19
Moisture (%)	5.7	9.4
Volatile matter (%)	84.45	64.7
Ash (%)	0.3	10.4
LHV ($MJ \cdot kg^{-1}$)	17.89	14.76
HHV ($MJ \cdot kg^{-1}$)	19.95	15.97

The tests were carried out with the use of a 10 kW automatically fed boiler by Greń (Pszczyna, Poland). Primary and secondary air was fed by a fan controlled by the boiler controller.

The exhaust gas flow rate was determined by the measurement of the gas velocity with an L-type Pitot tube (Testo SE & Co. KGaA, Titisee-Neustadt, Germany). Pellet consumption was measured during combustion using a scale placed under the stove platform. The test stand is shown in Figure 2 (a schematic is available in [6]).

After the boiler was started, the fuel dosage was gradually increased to achieve the rated operating parameters and a stable flue gas temperature, which was the criterion for achieving proper operating conditions. The boiler was then operated for 1 h at full load, during which the particulate emissions were monitored.

The TSP mass was measured using a particulate matter measurement system Testo 380 combined with Testo 330-2 LL (Testo SE & Co. KGaA, Germany). The analyzer's probe was mounted in the chimney on a straight section of the flue. The exhaust gas analyzer performed automatic measurements at a frequency of 10 s. In order to compare emissions, the results obtained in $mgNm^{-3}$ were converted to emission factors related to a unit of fuel mass (1) and a unit of energy (2):

$$EF_{PM} = \frac{C \cdot V_{Total}}{m_{fuel}}, \left(\mathrm{mg_{PM}} \cdot \mathrm{kg_{fuel}^{-1}}\right), \quad (1)$$

$$EF_{PM} = \frac{C \cdot V_{Total}}{m_{fuel} \cdot HHV}, \left(\mathrm{mg_{PM}} \cdot \mathrm{MJ^{-1}}\right), \quad (2)$$

where

C is the average concentration of PM ($mg \cdot m^{-3}$);
V_{Total} is the total volume of the gas sampled during the experiment (m^3);
m_{fuel} is the mass of dry fuel consumed (kg);
HHV is the higher heating value ($MJ \cdot kg^{-1}$).

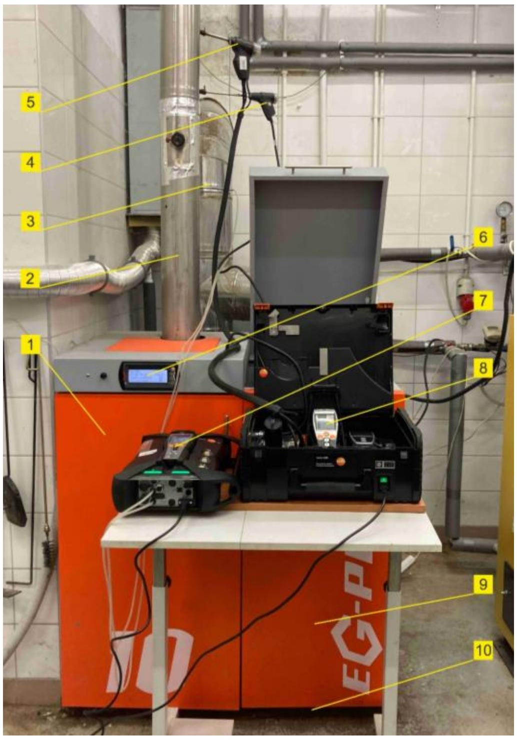

Figure 2. Boiler test stand: 1—test boiler, 2—chimney, 3—Pitot tube, 4—fume probe, 5—flow probe, 6—boiler controller, 7—Testo 350—flow meter, 8—Testo 380—PM meter, 9—pellet reservoir, 10—scales.

2.2. Engine Tests

Rapeseed biofuel FAME (fatty acid methyl esters)—B100 and Efecta Diesel Fuel—DF, were used in the study. Table 2 contains the selected physical and chemical properties of both fuels.

Table 2. Chosen characteristics of the tested fuels.

Parameter	DF	B100
Cetane number	51.4	52.1
Density @ 15 °C (kg·m^{-3})	835	883
Viscosity @ 40 °C (mm^2·s^{-1})	2.6	4.47
Flash point (°C)	69	120
FAME content (% w/w)	6.8	98.8
Carbon (%)	85.7	76.9
Hydrogen (%)	10.6	11.9
Oxygen (%)	2.4	10.3
LHV (MJ·kg^{-1})	43.51	37.92
HHV (MJ·kg^{-1})	45.84	40.36

The tests were carried out on a John Deere 4045TF285JD internal combustion engine mounted on a test stand equipped with an eddy current brake (Figure 3). A schematic of the stand is available in [6].

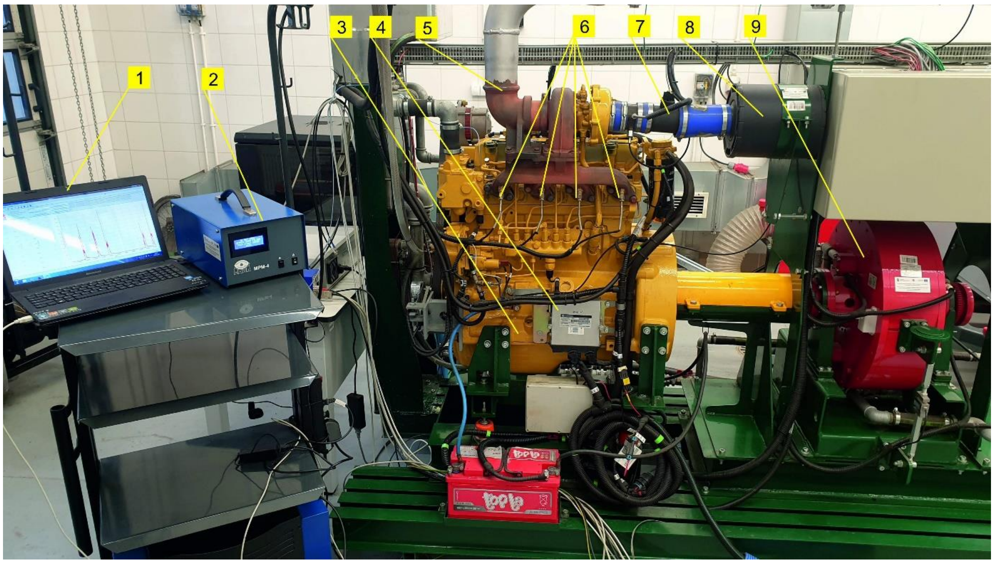

Figure 3. Engine dynamometer test stand: 1—PC-data recorder, 2—MPM4, 3—John Deere engine, 4—engine management unit, 5—exhaust fumes outport, 6—fumes temperature probes, 7—air flow meter, 8—air inlet filter, 9—eddy current engine brake.

An electromotor brake of the AMX—200/6000 type was mounted on the dynamometer bench, with a maximum absorbed power of 200 kW. A strain gauge actuator was mounted on an arm attached to the brake body. Engine speed was measured using an inductive sensor. The test stand was equipped with an ATMX2400 type gravimetric fuel gauge with fuel conditioning. It was also equipped with a system for indexing the engine and recording the rapidly varying pressures of the working medium in the cylinder. The dynamometer's control room, in addition to controlling the operation of the engine-brake unit, allowed for continuous recording of the measured parameters, their visualization, and storage in computer memory. The basic specifications of the tested engine are presented in Table 3.

Table 3. Chosen parameters of the John Deere 4045TF285JD engine.

Parameter	Characteristics
Engine type	Self-ignition engine
Engine displacement	4.5 dm^3
Injection system	direct injection
Fuel System	Mechanical governor
Aspiration	Turbocharged
Cylinder arrangement and number	In-Line, 4-Cycle
Compression ratio	19:1
Nominal power	74 kW
Nominal speed	2400 rpm
Peak torque	353 Nm
Peak torque speed	1600 rpm

Measurements of the PM content in the exhaust gases were carried out based on the engine load characteristics over the full load range, with speeds varying from 1400 to 2400 rpm, in 250 rpm increments. The study used the MPM4 particulate emission meter from MAHA, dedicated to continuous measurement of particulate matter emissions in the exhaust of automotive engines, particularly diesel engines.

The MPM4 meter uses a method of detecting monochromatic radiation (LLSP—laser light scattering photometry) reflected from particles in the exhaust gas, which is an alternative to gravimetric methods (Figure 4).

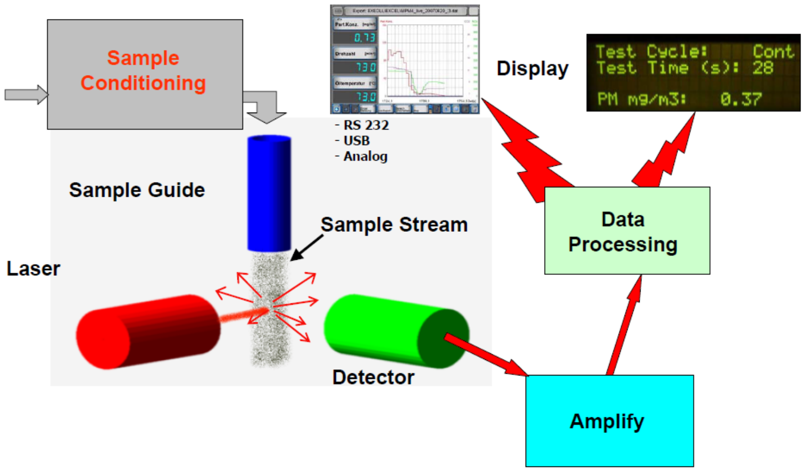

Figure 4. The idea of LLSP—laser light scattering photometry—method used in MPM4 (MPM4_New.pdf).

The measurement results are expressed in mg·m^{-3}. The measurement range was from 0 to 700 mg·m^{-3} and allowed for testing of both modern engines equipped with a diesel particulate filter (DPF) as well as older units and research engines without additional exhaust treatment [24].

2.3. Statistical Analysis

The obtained results of the boiler and engine tests were subjected to statistical analysis using the Statistica ver. 13 program (TIBCO Software Inc., Palo Alto, CA, USA, 2017). The influence of the type of fuel on the PM emission was analyzed using analysis of variance (ANOVA) at a significance level of α = 0.05.

3. Results and Discussion

3.1. Boiler Test Results

During the boiler test combustion of the tested biofuels, significantly higher PM emissions were found for the combustion of rapeseed straw pellets (Figure 5).

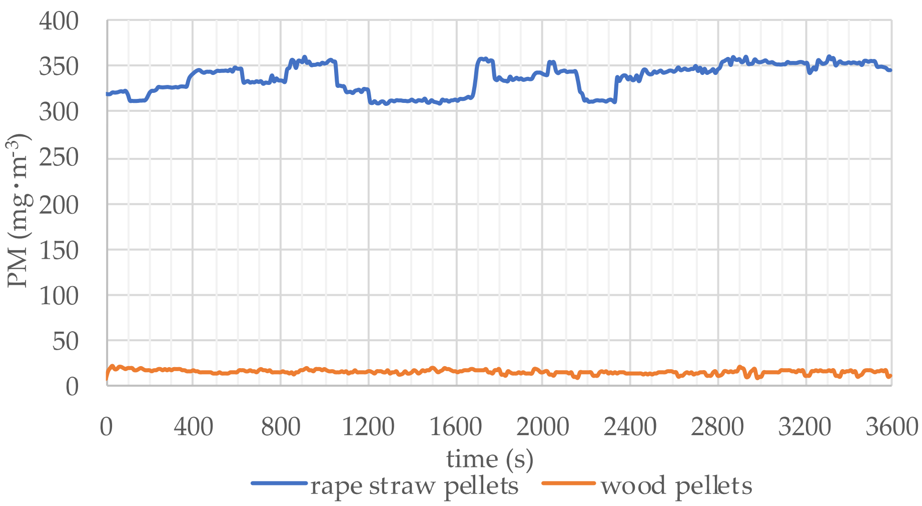

Figure 5. PM emissions during the tests of wood pellets and rapeseed straw pellets.

The average particulate matter emission during the tests of wood pellets was 15.45 mg·m^{-3}, while the average emission during the tests of rapeseed straw pellets was an order of magnitude higher, at 336.9 mg·m^{-3}. Thus, the values of PM emission during the tests of rapeseed straw pellets exceeded many times the emission values that occurred during the tests of wood pellets alone. This was confirmed by similar studies conducted by Chojnacki et al. [25], who found particulate emissions when burning pine pellets of 22.5 mg·m^{-3}, and 218.9 mg·m^{-3} when burning rapeseed straw petals. As reported by Young et al. [26], unlike wood, agricultural solid biofuel had a higher ash content (especially higher alkali metal content), which led to higher PM emissions. In their research, Carroll and Finnan [27] found that the total TSP emissions obtained during wood combustion were 22–51 mg·m^{-3}, while for rapeseed straw biomass, the value rose to 311–399 mg·m^{-3}; they also found similarly high TSP emission values for wheat straw of 253–281 mg·m^{-3}, and barley straw of 251–280 mg·m^{-3}. Garcia-Maraver et al. [28] found that the total particulate emissions ranged from 50 to 100 mg·m^{-3} when pine pellets were burned, while that value increased to 100–600 mg·m^{-3} when olive biomass waste pellets were burned. This was also confirmed in the work of [29], where higher TSP and PM10 emissions were related to agricultural and horticultural biomass combustion, and in the work of [30], where emissions during wood pellet combustion were 104–143 mg·m^{-3}, and during coffee ground pellet combustion, they were 1071–1472 mg·m^{-3}.

Differences in the chemical composition and ash content in the tested pellets resulted in significantly higher PM emissions during the combustion of rapeseed straw pellets.

As noted by [31], there is a significant variation in the chemical composition of biofuels made of different types of biomass. The content of alkali metals, chlorine, and sulfur is higher in cultivated plants than in woody biomass, which results from the cultivation conditions (fertilization).

On the other hand, wood biomass may contain a higher content of heavy metals, which is due to the long vegetation period of trees and the lower pH of forest soils, which increases the solubility of most heavy metal salts.

The tested pellets were also characterized by different humidity, although these differences were not significant. Rapeseed straw pellets (9.4%) had a higher humidity than the wood pellets (5.7%). However, in both cases, the humidity was at a level enabling the direct combustion of these biofuels (<20%) and below the maximum humidity ($\leq$10) specified in the standard ISO 17225-1:2021-11 for wood pellets.

In addition, the combustion of agrobiomass in grate furnaces encounters difficulties, because usually at a temperature of approx. 800 °C, slag is formed [32,33]. This phenomenon comes from the chemical composition of biomass and ash and makes the furnace operating difficult [34–36].

The best agrobiomass combustion technique is two-stage combustion (gasification and process gas combustion) [37]. However, the market lacks boilers with two-stage combustion with a capacity of up to 50 kW, designed to combust pellets of agrobiomass, which is why boilers with grate furnaces dedicated to wood pellets were used. However, in such situations, the combustion of agrobiomass can be problematic, because the temperature in the furnace often exceeds the sintering temperature of the agrobiomass ash and the slag is formed. Thus, the combustion temperature affects the formation of slag, which can also affect the level of PM emissions from the combustion of this type of fuel.

In order to compare and interpret the obtained test results and compare them with the literature reports, the EF emission factors were calculated related to the mass of fuel burned (mg·kg^{-1}) and energy obtained (mg·MJ^{-1}) (Table 4). Emission factors are a relative measure and can be used to assess emissions from various sources of air pollution. Their knowledge is important in developing pollution control strategies and assessing the practicability of burning a specific fuel.

Table 4. Emission factors determined for the tested pellets.

Specification	Wood Pellets	Rape Straw Pellets
PM (mg·m^{-3})	15.45	336.9
EF (mg·kg^{-1})	797	23,282
EF (mg·MJ^{-1})	44.5	1589

In the study in question, the rates were significantly higher for the combustion of rapeseed straw pellets, compared to the rates for woody pellets (Table 4). Available scientific publications report FE emission rates from the combustion of rapeseed straw to the order of 3700–13,000 mg·kg^{-1} [38], and from the combustion of wood pellets 430–1200 mg·kg^{-1} [39–41]. PM emission factors of biomass combustion expressed in units of mass per unit of energy are much more common in the literature. Chandrasekaran et al. [42] found that PM emissions resulting from grass pellet combustion were higher than received from woody pellets at both high (36–60 mg·MJ^{-1}) and low loads (26–40 mg·MJ^{-1}). In addition, the ash content of the fuel was strongly correlated with emissions of PM2.5. According to the literature reports [43], during the combustion of the currently used woody fuels, the amount of emitted particles ranged from 13 to 92 mg·MJ^{-1}. However, the combustion of grain biofuels (oat, rape seed, rape seed residue), in contrast to wood biofuels, resulted in significant emissions of the phosphate fraction of particulate matter. In continuous biomass-fired equipment, the content of alkali metals coming from the fuel is a major factor in particulate formation. Ozgen et al. [44], on the other hand, reported that in a study of boilers fired with various wood biofuels, PM emissions were significantly lower for automatic pellet-fired equipment than for manual (wood-fired) equipment at 85 g·GJ^{-1}, and the average particulate emission rates for wood pellets were 6–116 g·GJ^{-1} [45].

During the boiler tests conducted, high particle emissions associated with the combustion of rapeseed straw biomass pellets were found, which may discredit this biomass as a fuel for low-emission boilers. Consideration should therefore be given to the use of agrobiomass solid biofuels in larger capacity installations equipped with flue gas cleaning systems. Bearing in mind that pellet fuel generates lower particulate emissions than other types of wood fuels. According to [46], particulate emissions can be far from the emission limit when burning pellets made of wood in grate burners with electrostatic precipitators. Shen et al. [47] reported that biomass pellets can be a clean replacement for biomass in its traditional form. This indicates the need to study emissions from the combustion of biomass pellets.

Small-capacity boilers used for domestic heating are a significant source of particulate air pollution in the winter season. The efficiency of the dedusting devices should be higher than 95% to meet the ECOSOC emission limit and the emission level for a biomass lower than 20 mg·m^{-3}. Therefore, an urgent need has arisen to develop small flue gas cleaning devices dedicated for particulate matter produced by small domestic boilers, which could be integrated with such boilers [48].

3.2. Engine Test Results

During the testing of a John Deere engine fueled by FAME and comparatively by diesel fuel, the content of PM emissions in the exhausts was measured under varying load-speed conditions.

Figures 6–10 show the changes in the PM concentration in the engines' exhausts when operating over a range of load characteristics realized at 1400, 1650, 1900, 2150, and 2400 rpm, respectively.

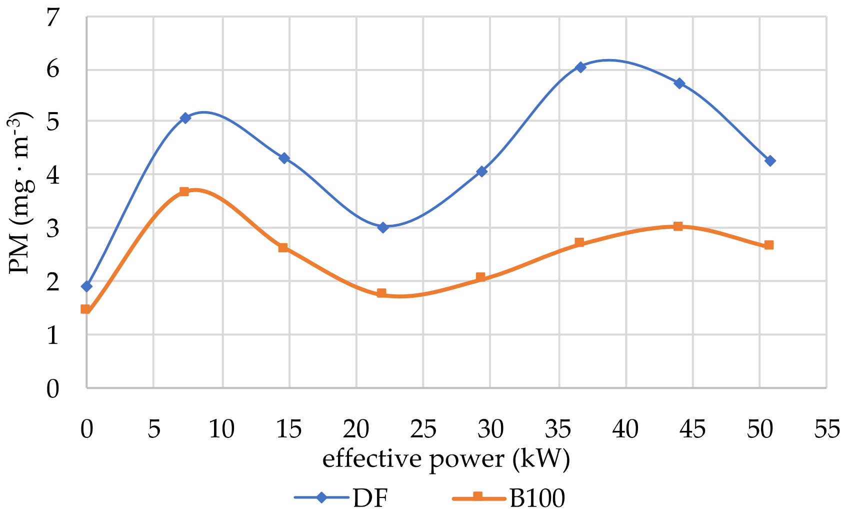

Figure 6. PM emissions vs. effective power of the John Deere 4045TF285JD engine at 1400 rpm.

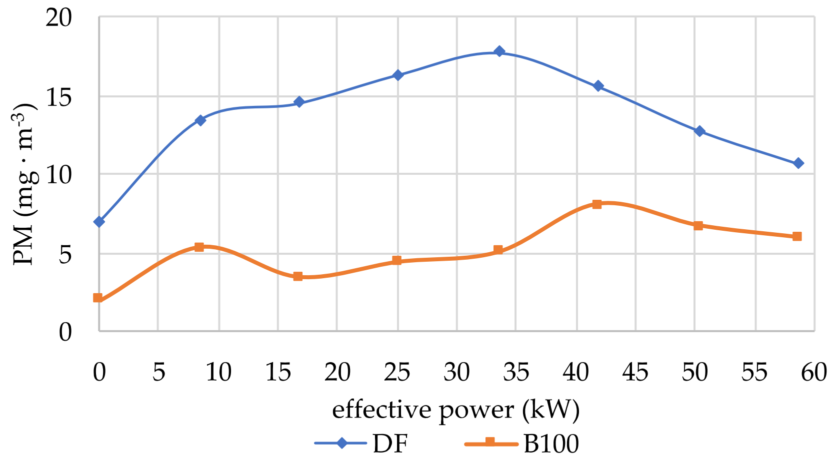

Figure 7. PM emissions vs. the effective power of the John Deere 4045TF285JD engine at 1650 rpm.

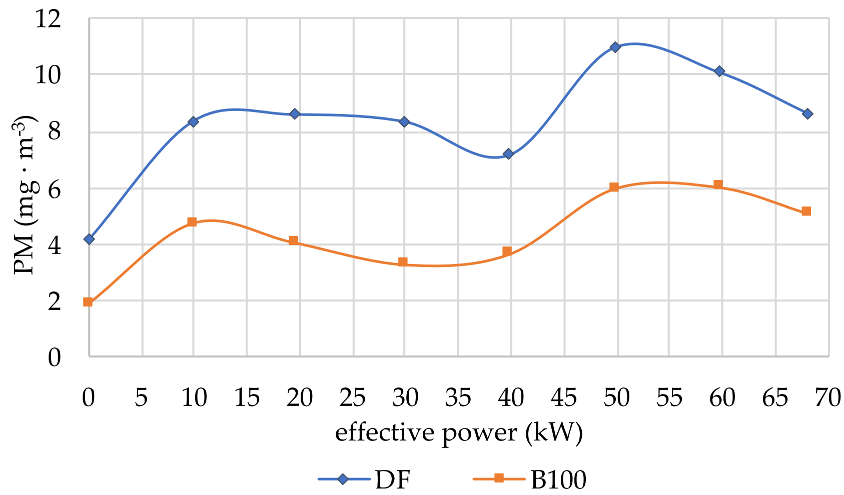

Figure 8. PM emissions vs. the effective power of the John Deere 4045TF285JD engine at 1900 rpm.

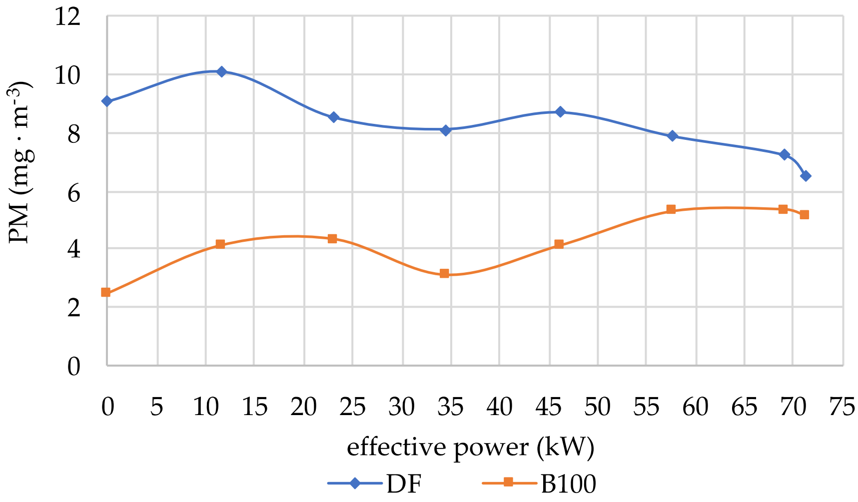

Figure 9. PM emissions vs. the effective power of the John Deere 4045TF285JD engine at 2150 rpm.

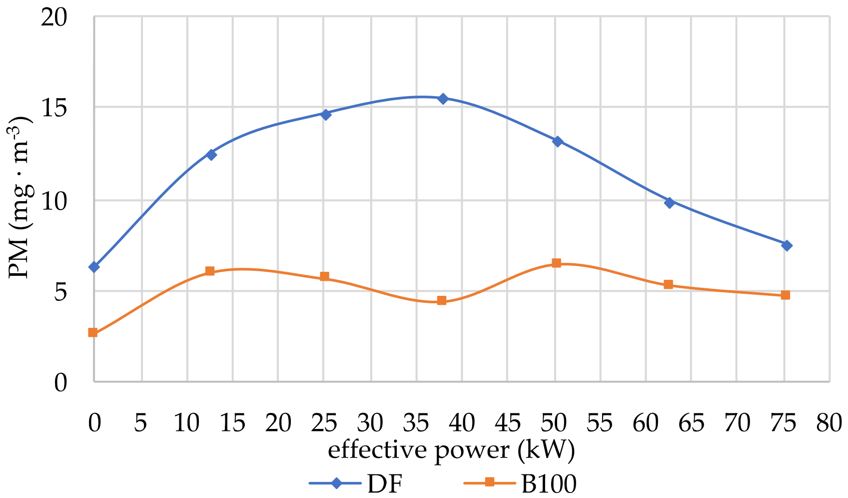

Figure 10. PM emissions vs. the effective power of the John Deere 4045TF285JD engine at 2400 rpm.

The tests showed significant reductions in PM emissions at all of the realized engine speeds for the biodiesel-fueled engine compared to the diesel-fueled one, averaging over 40% over the entire engine load range. The largest decrease in average PM emissions for biodiesel compared to diesel (61.1%) was recorded at 1650 rpm (i.e., corresponding to the highest engine torque (Figure 7)), and the smallest at 1400 rpm—40.3% (Figure 6). At a rated speed of 2400 rpm (Figure 10), the decrease in PM emissions of an engine fueled with B100 biofuel compared to a conventional fuel drive was 54.2% on average over the entire power range. At intermediate speeds of 1900 rpm (Figure 8) and 2150 rpm (Figure 8), the engine emitted less particulate matter when powered by biodiesel, averaging 48.2% and 46.9%, respectively, compared to DF. In the case of the B100 biofuel, for all rotational speeds, the lowest PM emission levels were observed for the operation of the no load engine operation. At the rated load for the considered speeds, the PM content in the exhaust gases of the engine fueled with biodiesel increased nearly three times. However, regardless of the load, the PM emissions for B100 each time were lower than that for the DF.

The significant decrease in the particulate matter content in the exhaust gases of the tested engine when fed with FAME was due to the high oxygen content in the biofuel (10.3%—Table 2). Such a significant oxygen share in the biofuel resulted in more complete combustion, which was bound with the reduced formation of PM.

In diesel engines, it is problematic to thoroughly mix the fuel with the oxygen contained in the air, which results in a local lack of oxygen and high-temperature breakdown of fuel particles, leading to the formation of particulate matter. Therefore, if part of the oxygen is supplied in the fuel, it will allow for more complete combustion and lower emissions of harmful exhaust components.

The significant environmental benefits of reducing diesel engine smoke when using rapeseed oil methyl esters have been confirmed in domestic and international studies. For example, the authors in [49,50] pointed to a nearly 50% reduction in PM emissions for the B100 biofuel compared to DF, confirming the downward trend in the emissions of this component in the studies conducted (a decrease of more than 40%). Other authors [51,52] have reported lower PM emissions for the B100 biofuel compared to DF in the range of 20–60%, which is also confirmed by the results of the studies included in this publication. However, the amount of particulate matter emitted is closely related to the specific engine (design features, technical condition, regulatory settings used, etc.) and the conditions under which it operates [53,54].

Table 5 presents the ANOVA results obtained for the measured PM emission levels in the boiler and engine tests.

Table 5. ANOVA results for PM emission levels (mg·m^{-3}) due to fuel.

Fumes' Component	Factor	Degrees of Freedom df	Totals of Squares SS	Medium Square MS	Test Function Value F	Calculated Significance Level p
PM	Fuel wood pellets and rapeseed straw pellets)	1	18,659,683	18,659,683	161,346.3	0
PM	Fuel DF and B100	1	460.6794	460.6794	50.28063	0

Statistical studies were carried out to confirm the observed differences in the particulate emission levels. The results of the analysis of variance obtained for the PM emission levels by type of pellet showed significant differences between the average values (at the significance level of $\alpha = 0.05$).

Similarly for the pellets, the results of the analysis of variance obtained for the PM emission levels by the type of liquid fuel (B100, DF) showed significant differences between the average values (at the significance level of $\alpha = 0.05$).

The statistical evaluation of the significance of the differences (ANOVA) presented in Table 5 completes and makes the comparison of particulate matter emissions more credible due to the biofuel used in both energy devices.

4. Conclusions

The negative aspects of emissions associated with the combustion of various biofuels may prevent their use as sustainable fuels. To overcome this disadvantage, detailed information is needed on particulate emissions from the combustion of different types of biofuels. This information will help identify the types of biomass and biofuels that emit more particles during combustion and can lead to measures to reduce this pollution [29]. The properties and applications of different types of biofuels vary widely, as do their advantages and disadvantages [55]. These properties can significantly affect the air quality associated with combustion processes [56]. The purpose of the boiler tests conducted was to analyze particulate emissions during the combustion of wood pellets and waste biomass pellets—rapeseed straw—in a low-power boiler. The results obtained indicate that the level of particulate emissions accompanying the combustion of wood pellets was significantly lower compared to the level of emissions recorded during the combustion of the rapeseed pellets, and at this stage, wood pellets are by far the better biofuel for individual household use. However, rapeseed straw should not be discredited as a biofuel as it can be burned in higher-capacity installations equipped with flue gas cleaning devices. Further research into the combustion process of this biofuel may contribute to improving the emission rates. The development of waste biomass such as rapeseed straw will allow for the sustainable and efficient use of rapeseed crops and a closed material cycle in the economy. In addition, it is important to develop another line of research concerning the equipping of small domestic boilers with integrated devices designed to purify flue gases from particulate matter.

Engine tests conducted under varying speed and load conditions showed clear environmental benefits associated with significantly lower levels of particulate matter emissions in the engine exhaust fueled by biodiesel (40–60%) compared to diesel fuel. Such a large reduction in PM emissions makes rapeseed oil esters a desirable choice as an engine fuel in the agricultural sector, among others. This is due to the fact that tractor engines burn significant amounts of fuel. In addition, tractor engines often operate at high loads, often rated, under which operating conditions the concentration of particulate matter in the exhaust is high. In addition, the authors' studies have shown other measurable environmental benefits of biodiesel as a diesel fuel such as with regard to methane, whose emissions when running on biofuel compared to diesel fuel have been reduced by 25–30% [6].

Given the wide variety of biofuels, there is a need to continue research on their optimal use in specific equipment or energy processes with the least possible environmental impact.

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