energies

MDPI

Article

Evaluation of Greenhouse Gas Emission Levels during the Combustion of Selected Types of Agricultural Biomass

Jacek Wasilewski, Grzegorz Zając *, Joanna Szyszlak-Bargłowicz and Andrzej Kuranc

Department of Power Engineering and Transportation, Faculty of Production Engineering, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland

* Correspondence: grzegorz.zajac@up.lublin.pl

Abstract: This paper presents the results of an experimental study of the emission levels of selected greenhouse gases (CO_2, CH_4, NO_x) arising from the combustion of different forms of biomass, i.e., solid biomass in the form of pellets and liquid biomass in the example of engine biofuel (biodiesel). Both types of biomass under study are rape-based biofuels. The pellets are made from rape straw, which, as a waste product, can be used for energy purposes. Additionally, biodiesel contains rape oil methyl esters (FAME) designed to power diesel engines. The boiler 25 kW was used to burn the pellets. Engine measurements were performed on a dynamometer bench on an S-4003 tractor engine. An analyzer Testo 350 was used to analyze the exhaust gas. CO_2 emission studies do not indicate the environmental benefits of using any alternative fuels tested compared to their conventional counterparts. In both the engine and boiler tests for NO_x emissions, no environmental benefits were demonstrated from the use of alternative fuels. The measured average NO_x emission levels for biodiesel compared to diesel were about 20% higher, and for rapeseed straw pellets, they were more than 60% higher compared to wood pellets. Only in the case of engine tests was significantly lower CH_4 (approx. 30%) emission found when feeding the engine with rape oil methyl esters.

Keywords: greenhouse gases (GHG); rape straw pellets; biodiesel; combustion; CO_2; CH_4; NO_x emission levels; pellet boiler; tractor engine

Citation: Wasilewski, J.; Zając, G.; Szyszlak-Bargłowicz, J.; Kuranc, A. Evaluation of Greenhouse Gas Emission Levels during the Combustion of Selected Types of Agricultural Biomass. *Energies* **2022**, *15*, 7335. https://doi.org/10.3390/en15197335

Academic Editors: Vadim Bolshev, Vladimir Panchenko, Nallapaneni Manoj Kumar, Pandian Vasant, Igor S. Litvinchev and Prasun Chakrabarti

Received: 14 September 2022
Accepted: 2 October 2022
Published: 6 October 2022

1. Introduction

The most serious global threats to the natural environment include the intensification of so-called greenhouse gas (GHG) emissions. The effect of this phenomenon's intensification is climatic changes of global character, caused by an increase in the temperature of the lower layers of the atmosphere as well as the surface of the Earth and surface waters [1].

Fossil fuel consumption is a major cause of climate change. In China, where coal-fired power plants dominate, the carbon emission factor is about 1.1 kg $CO_2 \cdot kWh^{-1}$. In the Tokyo area of Japan, the carbon emission factor is about 0.4 kg $CO_2 \cdot kWh^{-1}$, and in regions using hydropower, such as Brazil, it is 0.2 kg $CO_2 \cdot kWh^{-1}$ [2]. NO_x emission values are higher when burning coal fuels compared to other fuels, while CO_2 emissions are the highest when burning lignite [3]. A review of the environmental impact of electricity generation based on combustion technologies of different fuels [4] clearly indicates that hard coal combustion has the highest impact on global warming and ecotoxicity. Among fossil fuels, the highest CO_2 emission factors are characterized by lignite combustion (1300 $kg \cdot MWh^{-1}$), and the lowest are characterized by natural gas (550 $kg \cdot MWh^{-1}$). In contrast, the highest NO_x emissions are associated with the combustion of diesel fuel (75,000 $kg \cdot MWh^{-1}$), and the lowest are associated with natural gas and lignite (15,000 $kg \cdot MWh^{-1}$). For CH_4 emissions, the high emissions are associated with the combustion of hard coal and natural gas (15,000–20,000 $kg \cdot MWh^{-1}$).

Interest in bioenergy has increased in recent decades due to the increased awareness of climate change issues and ambitions to reduce the dependence on fossil fuels [5]. The use of biomass is one of the options for an emission-neutral greenhouse gas as an energy source. However, as [6] noted, carbon neutrality in terms of carbon emissions is not the same as climate neutrality.

Biofuels can reduce the use of fossil fuels and thus reduce greenhouse gas emissions. The impact of biofuel use on mitigating climate change and reducing dependence on fossil fuels is the subject of intense debate in the scientific community. The actual benefits may be limited by local geographic factors, biofuel production technology, and the energy system used.

The use of biomass for energy production carries the risk of increasing emissions of GHG into the atmosphere. According to [7], biomass combustion, including residential biomass combustion (RBC), is a significant global source of gaseous emissions. Biomass combustion is the third largest source of CH_4, contributing to global methane emissions of approximately 40 Tg per year [8] and thus having a direct impact on the global CH_4 balance due to its long residence in the troposphere. Biomass combustion also emits nitrous oxide N_2O. Reactive nitrogen compounds have a significant impact on the chemistry of the atmosphere. This gas has a higher ability to absorb and remit terrestrial radiation than CO_2 or CH_4, so it is a more potent greenhouse gas.

Another use of biomass is biofuels for transportation. Vegetable oils or animal fats are converted to biodiesel through the transesterification with methanol, resulting in a mixture of fatty acid methyl esters (FAME) [9], which are used as an alternative fuel for feeding internal combustion engines [10]. Although the new guidelines mandate that biodiesel be derived from non-food raw materials, for Central Europe and countries with similar climatic conditions, the most promising is the use of biodiesel based on rape oil [11]. In the process of obtaining rapeseed oil, there is waste generated in the form of rapeseed straw, which can be utilized for energy purposes. Some researches [12,13] found out that rape straw is a valuable energy raw material of high calorific value. Redundant rape straw can become raw material for the production of compact solid biofuels [14] as an alternative to wood pellets used in low-power boilers with automatic loading. This policy is in line with one of the objectives of the EU Common Agricultural Policy, which is to promote agricultural practices that help protect the environment and climate.

The paper [15] outlines a number of positive and negative sustainability considerations associated with the removal of crop residues for expanded uses. As the authors point out, before using crop residues for biofuel production, it should be verified that neutral or positive sustainability impacts can be maintained under site-specific conditions. Crop residues from primary crops are available in significant quantities and do not compete with food production, and to some extent, they are created by virgin cereals production. As a result, there is no need for land conversion. However, this potential largely depends on the development of sustainable and efficient bioenergy systems [15].

Although there are many publications available on the emissions from both biodiesel and rape straw pellets, there is a lack of a comprehensive reference to the impact of the use of these biofuels on GHG emissions in exhaust gases concerning traditional fuels. Therefore, this study aimed to analyze the emissions of selected greenhouse gases (CO_2, CH_4, NO_x) generated during the combustion of different types of biofuels derived from the same plant, i.e., rape (rape oil methyl esters and rape straw pellets), in comparison with conventional fuels (diesel and wood pellets). The obtained results of the emission studies can demonstrate the environmental benefits of using alternative fuels in comparison with their typical counterparts

2. Materials and Methods

2.1. Boiler Tests

The fuels tested were rape straw pellets and A1-grade wood pellets available on the market. The physicochemical properties of rape straw pellets and wood pellets are presented in Table 1.

Table 1. Physicochemical properties of wood pellets and rape straw pellets.

Parameter	Symbol	Unit	Wood Pellets	Rape Straw Pellets
Moisture	W_t^r	%	5.7	9.4
Ash	A^a	%	0.3	10.4
Volatile matter	V^{daf}	%	84.45	64.7
Carbon	C^a	%	49.5	40.1
Hydrogen	H^a	%	6.06	5.8
Sulphur	$S^a{}_A$	%	0.02	0.31
Nitrogen	N^a	%	0.17	0.8
Oxygen *	O	%	38.25	33.19
HHV	$Q_s{}^a$	$kJ \cdot kg^{-1}$	19,953	15,972
LHV	$Q_i{}^r$	$kJ \cdot kg^{-1}$	17,893	14,763

* Oxygen was calculated as a complement.

In order to test the combustion of rape straw pellets and wood pellets, a 25 kW boiler adapted for burning pellets was used. The boiler was equipped with a furnace, to which fuel was fed from a reservoir in an automated way. Boiler operation was controlled by a programmed electronic controller. A diagram of the boiler stand is shown in Figure 1.

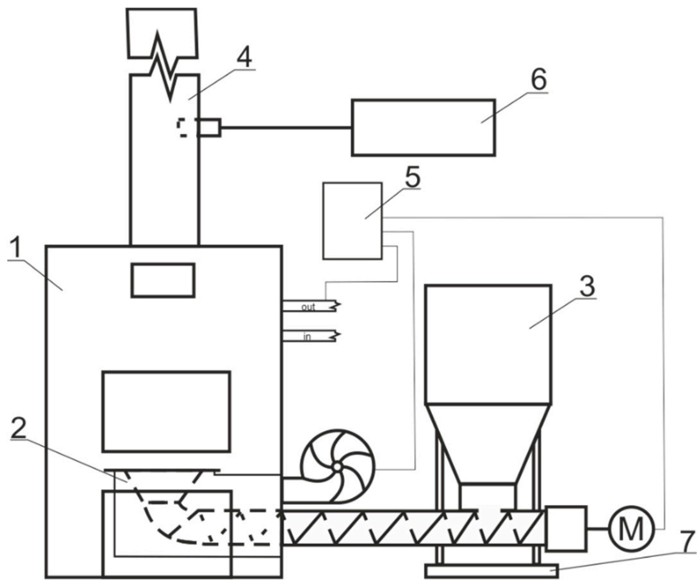

Figure 1. Scheme of boiler stand: 1—test boiler, 2—furnace, 3—pellet reservoir, 4—chimney, 5—boiler controller, 6—exhaust gas analyzer, 7—scales.

Boiler operation was controlled by a programmed electronic controller. The amount of fuel fed for combustion as well as the amount of air required for proper combustion was automatically selected by the controller, based on the results of measurements of the oxygen content in the flue gas provided by the lambda probe and the temperature sensor at the boiler outlet. Combustion tests were carried out under fixed boiler operating conditions at rated settings. Before starting the measurements, the boiler was warmed up for a period of 1 h, the time required to stabilize the boiler was not included in the test duration. The combustion test of individual pellets lasted for 1 h. The fuel consumption was determined by weighing the fuel fed into the reservoir before and after the test for each fuel. The fuel mass flux was, for wood pellets, 6.15 $kg \cdot h^{-1}$ and, for rapeseed straw pellets, 7.63 kg h^{-1}. The flue gas temperature was 138 °C and 134 °C, respectively.

2.2. Engine Testing

B100 biodiesel (fatty acid methyl esters FAME) and ON Efecta Diesel were used for the engine testing (Table 2).

Table 2. Selected physicochemical properties of diesel fuel and methyl esters rape oil.

Parameter	Symbol	Unit	B100	DF
Ester Content	FAME	% (m/m)	98.8	6.8
Density at 15 °C	ρ	kg/m^3	883	835
Viscosity at 40 °C	η	mm^2/s	4.47	2.6
Cetane Number	CN	-	52.1	51.4
Flash point	FP	°C	120	69
Carbon	H^a	% (m/m)	76.9	85.7
Hydrogen	$S^a{}_A$	% (m/m)	11.9	10.6
Oxygen	O	% (m/m)	10.3	2.4
HHV	$Q_s{}^a$	kJ/kg	40,365	45,839
LHV	$Q_i{}^r$	kJ/kg	37,918	43,511

The tests were carried out on a type S-4003 internal combustion engine installed on a dynamometer (Figure 2). The characteristic technical data of the tested engine are presented in Table 3. Despite the successive replacement of the machine park in Polish agriculture with modern tractors characterized by advanced operation and emission parameters, engines like the one under study are still being used to a considerable extent and pose potential ecological problems [16].

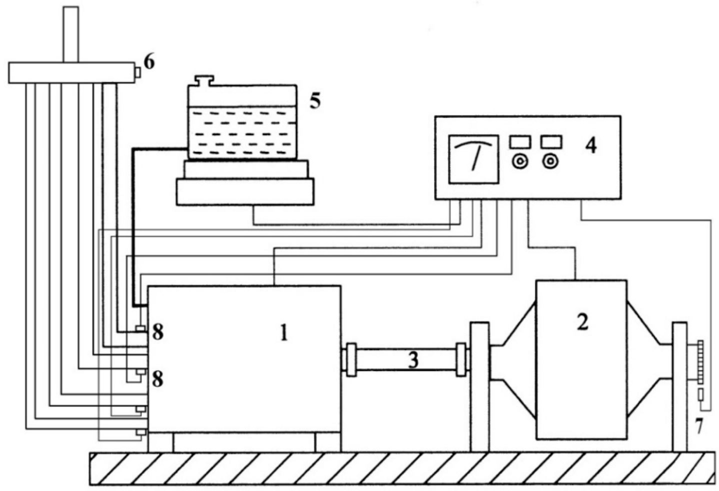

Figure 2. Scheme of the dynamometer stand: 1—test engine, 2—load brake, 3—shaft connecting the engine to the brake, 4—control and measurement system, 5—fuel consumption measuring system, 6—exhaust gas intake, 7—induction speed sensor, 8—exhaust gas temperature sensors.

Table 3. Basic technical data of the S-4003 engine.

Parameter	Unit	Characteristics
Type	-	Self-ignition engine
Cylinder arrangement	-	Vertical in-line
Number of cylinders	-	4
Operating system	-	Four-stroke
Injection system	-	Direct injection
Compression ratio	-	17:1
Engine displacement	dm^3	3.12
Rated power	kW	38.3
Rated speed	rpm	2200
Maximum torque	Nm	186
Maximum torque speed	rpm	1500–1600

Engine load shifting was accomplished with an electric brake type K1-136B-E (asynchronous ring generator), which was also used to start the engine. Emissions were measured based on engine load characteristics at two characteristic speeds (maximum torque and rated power) over the full load range [17,18].

2.3. Measuring Apparatus for Emission Tests

The concentrations of nitrogen oxides (NO_x), carbon dioxide (CO_2), and methane (CH_4) were measured using Testo 350. Testo 350 is a portable exhaust gas analysis system for the measurement of exhaust gas emissions.

2.4. Statistical Analysis

The obtained results were analyzed with the use of analysis of variance (ANOVA). The data analysis was carried out using the Statistica ver. 13 software (TIBCO Software Inc., Palo Alto, CA, USA, 2017) at a significance level of $\alpha < 0.05$.

3. Results and Discussion

3.1. Boiler Test Results

Figures 3–5 show the time courses of changes in CO_2, NO_x, and CH_4 concentrations accompanying the combustion of rape straw pellets and wood pellets. Table 4 lists the average concentrations of the measured flue gas components, calculated from the time courses of their changes. Moreover, Table 5 compares the emissions of these compounds during the combustion of the analyzed fuels in relation to the obtained heat energy.

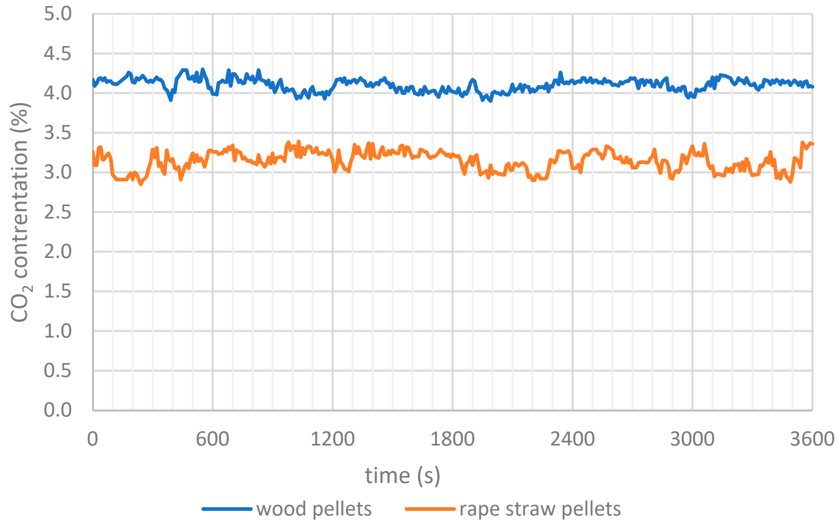

Figure 3. Time course of changes in CO_2 concentration for combustion tests of wood pellets and rape straw pellets.

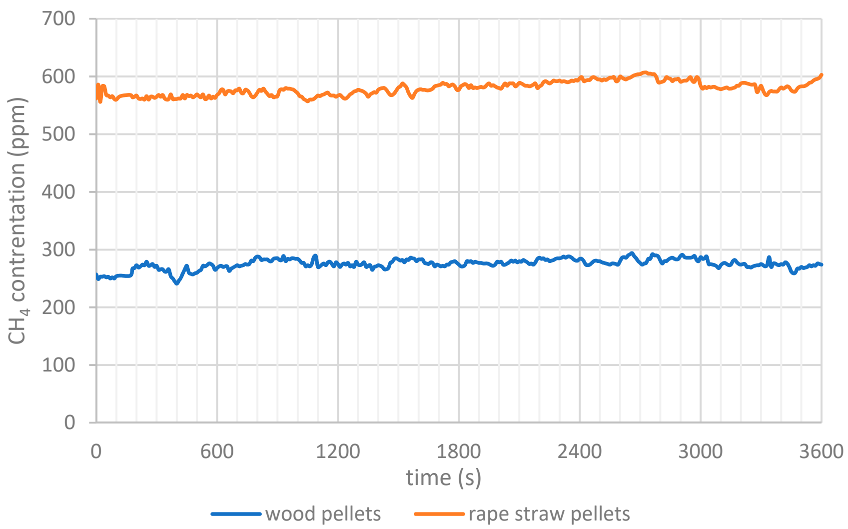

Figure 4. Time course of changes in CH_4 concentration for combustion tests of wood pellets and rape straw pellets.

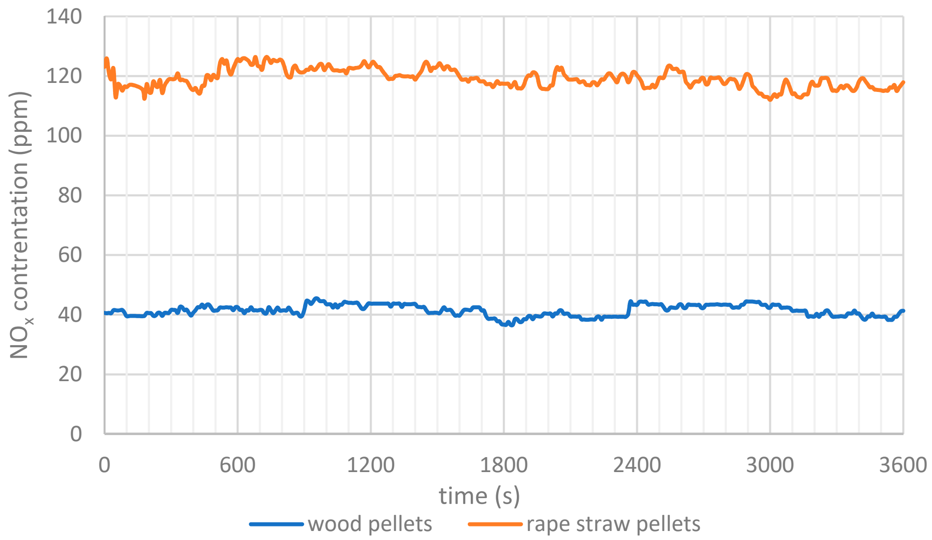

Figure 5. Time course of changes in NO_x concentration for combustion tests of wood pellets and rape straw pellets.

Table 4. Average concentrations of the measured flue gas components.

Specification	Unit	Wood Pellets	Rape Straw Pellets
CO_2	%	4.10	3.15
NO_x	ppm	41.4	119.2
CH_4	ppm	275.3	579.6

Table 5. Average emissions of GHG components (g·kWh^{-1}).

Emitted Fumes' Component	Units	Wood Pellets	Rape Straw Pellets
CO_2		432	439
NO_x	g·kWh^{-1}	0.33	0.96
CH_4		1.09	2.29

By comparing the concentrations of the tested gases presented in Figures 3–5 and the average concentrations presented in Table 4, it was found that, in the case of burning pellets from rape straw, the concentrations of CO_2 were lower those of than wood pellets, while the concentrations of NO_x and CH_4 were higher. Especially high concentrations were found for NO_x (almost three times higher) and CH_4 (two times higher for rape straw pellet combustion). The lower values of CO_2 content may be due to the lower calorific value and the higher moisture content of rape straw pellets compared to wood pellets. On the other hand, the higher NO_x concentration was caused by high nitrogen and oxygen contents in rape fuel. The high concentration of CH_4 in the flue gas also indicates an imperfect combustion process—incomplete combustion.

The results of the study presented in Table 5 confirm that the combustion of rape straw pellets is associated with higher NO_x and CH_4 emissions and lower CO_2 emissions in relation to the thermal energy obtained. By comparing the nitrogen content of rape straw pellets (Table 1) with the values typical for wood biomass, which, according to the literature, are below 0.2% [19], it is possible to notice a relatively high content of this element in rape straw pellets. This may be associated with the use of nitrogen-containing mineral fertilizers during rape cultivation, which adversely affects the NO_x emission during the combustion of the investigated biomass. This fact is confirmed by the results of energy and emission studies (NO 421.7 mg·m$_n$$^{-3}$, NO_2 664.8 mg·m$_n$$^{-3}$) (Tables 4 and 5, Figures 2–4).

The NO_x concentration found in the study [20] did not exceed 400 mg·m^{-3}. If the temperature in the furnace is relatively low, the NO_x concentration depends mainly on the nitrogen stream supplied to the furnace with the fuel, and nitrogen oxides are formed from nitrogen contained in the fuel [21]. In small power boilers, the combustion temperature very often does not exceed 1300 °C, and NO_x are not formed due to the oxidation of atmospheric nitrogen [22–24]. In this case, NO_x emissions should be directly related to the nitrogen content of the fuel.

However, due to the very high ash content in agricultural biomass, when considering the formation of NO_x during its combustion, the catalytic effects of the ash surface must also be taken into consideration. The different NO_x emissions during the combustion of pellets from agricultural biomass may be due to the varying nitrogen content of the biofuel as well as the ash catalyzing the formation of NO_x [25].

Table 6 shows the ANOVA results obtained for the measured emission levels of greenhouse gases, and in Table 7, they were converted to the unit of mass referred to as kWh in boiler tests.

Table 6. ANOVA results for the emission levels (volumetric shares) of GHG components by fuel (rapeseed straw pellets, wood pellets).

GHG Component	Factor	Degrees of Freedom df	Totals of Squares SS	Medium Square MS	Test Function Value F	Calculated Significance Level *p*
CO_2	fuel	1	163.2181	163.2181	15,593.84	0
NO_x	fuel	1	1,080,143	1,080,143	156,755.5	0
CH_4	fuel	1	16,528,891	16,528,891	151,205.4	0

Table 7. ANOVA results for the emission levels of GHG components ($g \cdot kWh^{-1}$) by fuel (rapeseed straw pellets, wood pellets).

GHG Component	Factor	Degrees of Freedom df	Totals of Squares SS	Medium Square MS	Test Function Value F	Calculated Significance Level *p*
CO_2	fuel	1	1.1×10^{10}	1.1×10^{10}	2554.695	0
NO_x	fuel	1	70,670,641	70,670,641	37,051.95	0
CH_4	fuel	1	16.279	16.279	24,133.99	0

In both cases, the results of the statistical analysis calculated using the analysis of variance method for all analyzed GHGs due to the type of pellet showed significant differences between the average values (at the significance level of $\alpha = 0.05$). Similar dynamics of changes in the content of the studied flue gas components were observed.

3.2. Engine Test Results

During the tests of the S-4003 engine on a dynamometer bench using FAME fuel and diesel fuel, emissions were measured under various speed-load conditions. Figures 6 and 7 show the waveforms of changes in the level of CO_2 emissions in the exhaust gas of the engine operating according to load characteristics, performed at 1600 rpm and 2200 rpm, respectively.

The study showed a slight decrease in CO_2 emission levels for biofuel, compared to ON, at both engine speeds (Figures 6 and 7). The largest difference between the average values of the concentration of this component in the exhaust gas over the entire engine load range (2.92%), was recorded between B100 and ON at the rated speed (2200 rpm). Figures 8 and 9 show the waveforms of changes in NO_x content in the exhaust gas as a function of engine load (effective power) for 1600 rpm and 2200 rpm, respectively. The study showed that feeding the engine with biodiesel increased in the concentration of nitrogen oxides in the exhaust gas compared to diesel fuel. Averaged over the entire engine load range, the increase in exhaust NO_x concentration was 19.8% at 1600 rpm and 18.9% at 2200 rpm. The level of CH_4 emissions in the exhaust gas (Figures 10 and 11) was found to be significantly lower for the ester-fueled engine compared to the diesel powertrain, averaging over the entire power range by 26.8% at 1600 rpm and by 29.3% at 2200 rpm.

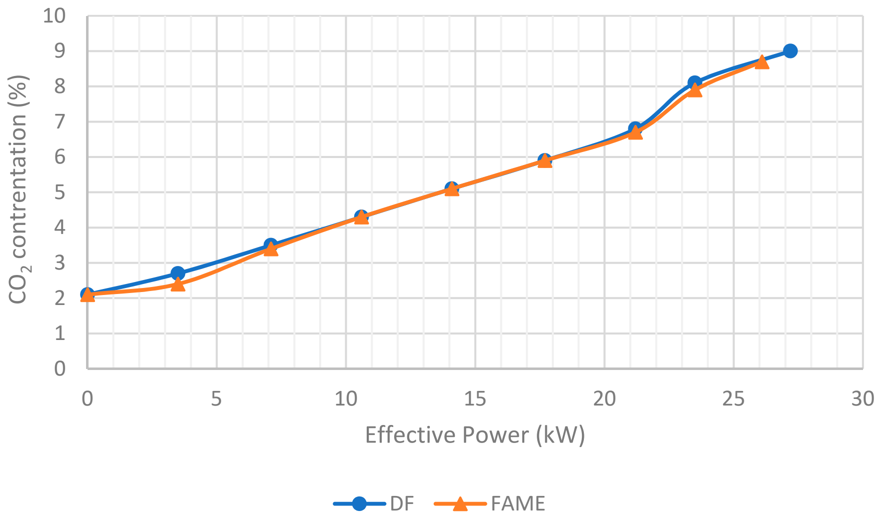

Figure 6. CO_2 emission level in the exhaust gas as a function of the effective power of the S-4003 engine, at an engine speed of 1600 rpm.

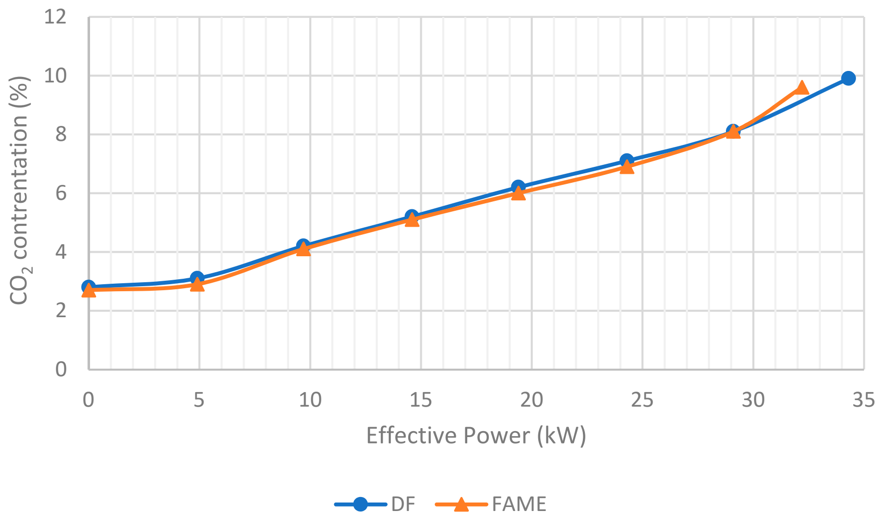

Figure 7. CO_2 emission level in the exhaust gas as a function of the effective power of the S-4003 engine, at an engine speed of 2200 rpm.

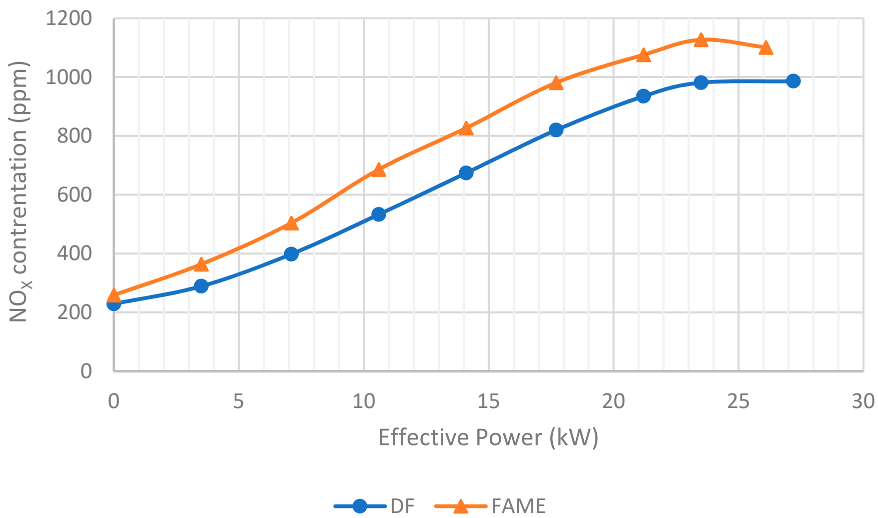

Figure 8. NO_x emission level in the exhaust gas as a function of the effective power of the S-4003 engine, at an engine speed of 1600 rpm.

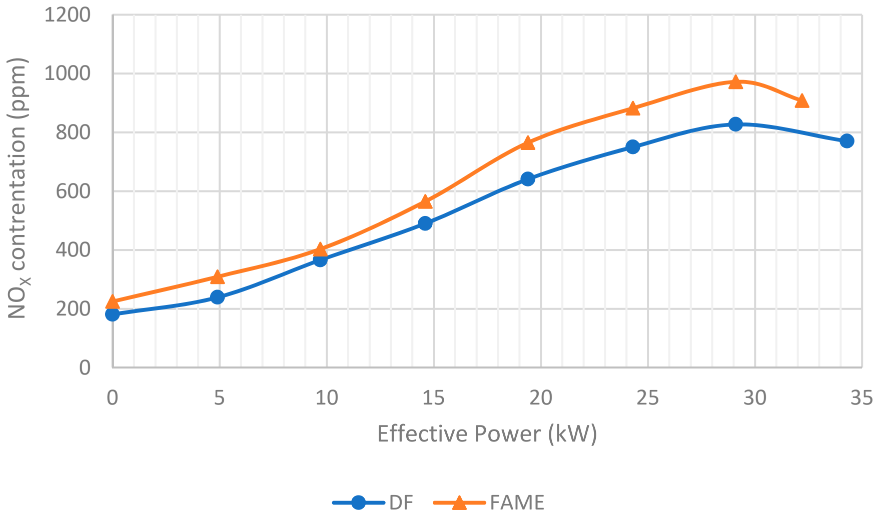

Figure 9. NO_x emission level in the exhaust as a function of the effective power of the S-4003 engine, at an engine speed of 2200 rpm.

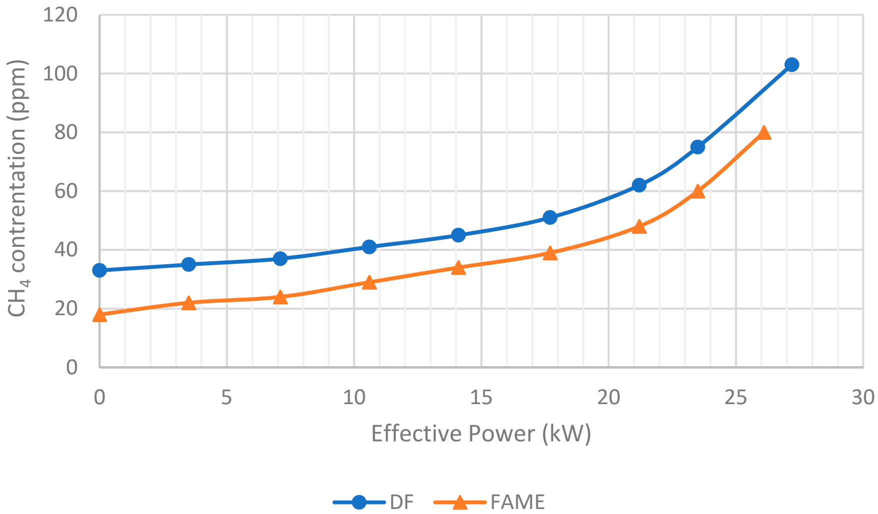

Figure 10. CH_4 emission level in the exhaust as a function of the effective power of the S-4003 engine, at an engine speed of 1600 rpm.

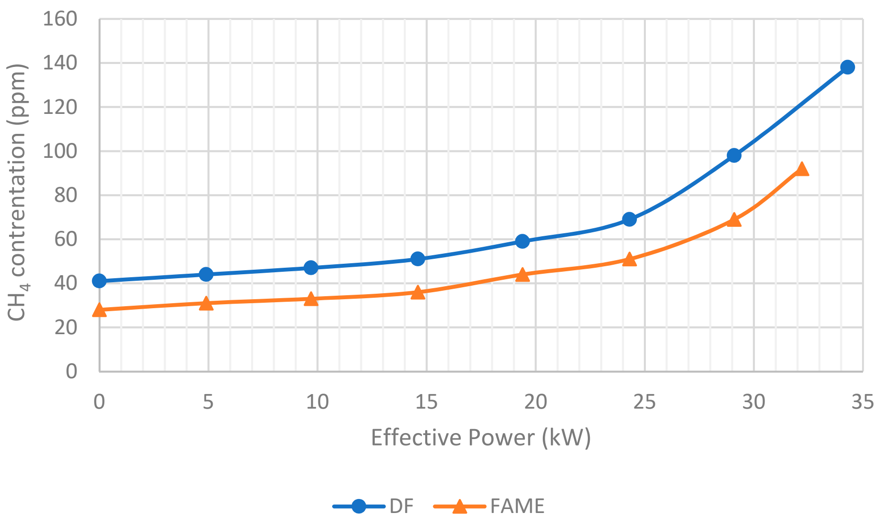

Figure 11. CH_4 emission level in the exhaust as a function of the effective power of the S-4003 engine, at an engine speed of 2200 rpm.

Effective power is one of the most important indicators of an engine's operation, as it determines the amount of energy given up to the consumer at each moment. As the effective power changes, the components of the exhaust gas change significantly, as demonstrated in the study (Figures 6–11). The measurements further showed that feeding the engine with biodiesel, compared to the ON drive, resulted in a decrease in effective power (evident at a full engine load) by 4.1% at 1600 rpm and by 6.1% at 2200 rpm. A particularly important engine operating parameter is effective (overall) efficiency, which characterizes the amount of heat energy supplied to the engine that is converted into useful (effective) work. Internal combustion engines typically have efficiencies of 30–40%. The highest effective efficiency (33%) was achieved by the tested biodiesel-fueled engine in the range of maximum torque characteristics.

GHG emissions are closely related to the temperature inside the cylinders and then, in the exhaust system, to the temperature of the exhaust gas. Exhaust gas temperatures measured during the tests varied from more than 100 °C at no-load engine operation to nearly 600 °C at full-load operation. A slightly higher average exhaust gas temperature, on the order of 1–2%, was recorded when the engine was fueled with biodiesel. Table 8 shows the emissions of measured GHG components converted to $g \cdot kWh^{-1}$ according to the calculation methodology in the works of [26,27].

Table 8. Level of emissions of GHG components ($g \cdot kWh^{-1}$) due to fuel and engine speed (rpm) and power output (kW).

B100					ON				
Speed rpm	**Power Output kW**	**CO_2 $g \cdot kWh^{-1}$**	**NO_x $g \cdot kWh^{-1}$**	**CH_4 $g \cdot kWh^{-1}$**	**Speed rpm**	**Power Output kW**	**CO_2 $g \cdot kWh^{-1}$**	**NO_x $g \cdot kWh^{-1}$**	**CH_4 $g \cdot kWh^{-1}$**
1600	0	-	-	-	1600	0	-	-	-
	3.5	2161.0	24.5	3.4		3.5	2063.0	20.9	5.9
	7.1	1275.0	15.4	1.7		7.1	1244.5	12.3	2.6
	10.6	1024.7	13.7	1.4		10.6	998.6	10.4	1.9
	14.1	912.5	12.4	1.2		14.1	896.2	10.0	1.5
	17.7	863.7	12.1	1.1		17.7	881.3	10.3	1.5
	21.2	871.0	11.8	1.2		21.2	868.0	10.0	1.5
	23.5	883.7	10.6	1.3		23.5	881.2	9.0	1.6
	26.1	1019.2	10.8	1.8		27.2	950.1	8.8	2.1
2200	0	-	-	-	2200	0	-	-	-
	4.9	2364.8	21.2	4.9		4.9	2193.8	14.2	6.1
	9.7	1480.0	12.2	2.3		9.7	1400.1	10.3	3.1
	14.6	1195.7	11.1	1.6		14.6	1146.2	9.1	2.2
	19.4	1059.2	11.4	1.5		19.4	1011.5	8.8	1.9
	24.3	988.6	10.6	1.4		24.3	985.2	8.8	1.9
	29.1	1019.5	10.3	1.7		29.1	1001.5	8.6	2.4
	32.2	1106.8	8.8	2.1		34.3	1070.1	7.0	2.9

It can be seen from Table 8 that NO_x and CH_4 exhaust emissions expressed in $g \cdot kWh^{-1}$ showed the same trend of change as the measured values (in ppm), i.e., an increase and a decrease, respectively, in these two exhaust compounds when the engine was fed with B100 biofuel compared to ON. The average over the entire engine power range increase in NO_x was 21.8% at 1600 rpm and 26.5% at 2200 rpm, while the average decrease in CH_4 was 25.4% (1600 rpm) and 25.1% (2200 rpm). In the case of CO_2, however, higher mass emissions were obtained for biodiesel than for diesel, averaging 2.2% at 1600 rpm and 4.0% at 2200 rpm. This is mainly due to the higher fuel consumption and lower heating value of the B100 bioester compared to ON.

Table 9 shows the ANOVA results obtained for the measured GHG emissions in the engine tests.

Table 9. ANOVA results for emission levels (volume shares) of GHG components due to fuel and engine speed (biodiesel, ON).

GHG Component	Factor	Degrees of Freedom df	Totals of Squares SS	Medium Square MS	Test Function Value F	Calculated Significance Level *p*
CO_2	fuel	1	0.057647	0.057647	0.010419	0.919335
	speed rpm	1	2.359477	2.359477	0.432062	0.515679
NO_x	fuel	1	100,118.4	100,118.4	1.151727	0.291214
	speed rpm	1	140,155.9	140,155.9	1.63585	0.210093
CH_4	fuel	1	2647.059	2647.059	4.195462	0.048811
	speed rpm	1	1152.941	1152.941	1.701444	0.201403

The results of the statistical analysis calculated by the analysis of variance showed a significant effect of fuel type ($p < 0.05$) only for CH_4. For all the other cases analyzed, the differences in the averages are not statistically significant. Table 10 shows the ANOVA results obtained for the emission levels of the studied GHG components converted to $g \cdot kWh^{-1}$ in the engine tests.

Table 10. ANOVA results for the GHG component emissions ($g \cdot kWh^{-1}$) due to fuel and engine speed (biodiesel, ON).

GHG Component	Factor	Degrees of Freedom df	Totals of Squares SS	Medium Square MS	Test Function Value F	Calculated Significance Level *p*
CO_2	fuel	1	13,402.76	13,402.76	0.070184	0.79301
	speed rpm	1	200,098.5	200,098.5	1.121286	0.298382
NO_x	fuel	1	49.152	49.152	3.352122	0.077781
	speed rpm	1	29.16259	29.16259	1.924114	0.175973
CH_4	fuel	1	3.675	3.675	2.322869	0.138701
	speed rpm	1	2.417044	2.417044	1.537817	0.224884

The results of the statistical analysis calculated using the analysis of variance method for all the cases analyzed (Table 9) showed that the differences in the averages are not statistically significant (at the significance level of $\alpha = 0.05$). A valuable advantage of using biodiesel compared to diesel fuel is the reduced emission of particulate matter and the gaseous components of the exhaust gas (CO, HC), along with the excessive NO_x emissions, as demonstrated in numerous studies, both domestic and foreign. For example, in the work of the authors [28,29], the increase in NO_x concentration for B100 fuel compared to ON was about 10%, confirming the upward trend of this component of the exhaust gas in the completed studies (an increase of about 20%). In turn, the same researchers found a significant decrease in hydrocarbon emissions (about 60%) for B100 fuel compared to ON, which also confirms the results of the present study concerning methane (a decrease in the range of 25–30%). It should be noticed that the performance of an engine depends on its design features (shape of the combustion chamber, design of the fuel injection system, design of the intake system) and operational features (type and characteristics of the fuel, technical condition of individual engine systems, adopted control settings) [30–33]. According to the authors [34], comparing the Life Cycle Assessment (LCA) of biodiesel to that of diesel, the use of this biofuel is more beneficial in terms of reducing the overall greenhouse effect, CO_2 emissions, or carcinogenic compounds. In terms of CO_2, the researchers found that burning each ton of diesel fuel emits 2.8 tons of CO_2 into the atmosphere, while burning biodiesel emits 2.4 tons of CO_2/ton of bioesters. Energy crops are expected to expand significantly in the very short term, bringing significant social and environmental benefits. However, many studies indicate either very positive or negative environmental effects of energy crop cultivation and processing, so there is still a lot of uncertainty regarding these issues [35]. When considering the highest degree of greenhouse gas emission reductions accompanying the use of biomass for energy [36], first-generation biodiesel was found to have less of an impact than first-generation bioethanol concerning bioenergy systems. In addition, for first-generation biodiesel, sunflower showed a lower energy impact than rape. To minimize greenhouse gas emissions from energy systems, an analysis was conducted [37], which indicates that, with adequate biomass availability, liquid fuel production should be based on agricultural residues. Electricity production should be based on forest residues and other woody biomass, and heat production should be based on forest and agricultural residues.

The targets set by the 2009 Renewable Energy Directive for renewable energy make the EU a major global source of demand for biomass. Demand for biomass energy is likely to increase as EU member states set increasingly ambitious renewable energy targets. While biomass power generation is steadily being displaced by other renewable energy sources (mainly wind and photovoltaic power), biomass is likely to remain a major source of renewable heat and transportation biofuels in the short term [38]. The closed-loop economy allows for treating waste biomass as a potential source of valuable energy raw materials. The transition to a closed-loop economy requires, among other things, new ways of transforming hitherto unused waste into new products that constitute resources such as energy. Nevertheless, sustainability criteria should be considered to distinguish raw materials with different climate impacts, as burning different types of biofuels can generate GHG emissions. It is therefore important to control the types of biomass used in order to reduce their negative impact on the climate. Financial and regulatory support should be limited to those raw materials that reduce GHG emissions in the short term, such as lumber residues, agricultural production waste, and post-consumer waste. The overarching goal is to develop sustainable energy systems that do not contribute to further climate change or negatively impact other aspects of sustainability.

4. Conclusions

The novelty of the paper is a comparative study of GHG emissions from the combustion of biodiesel and diesel in an internal combustion engine and from the combustion of various solid biofuels (rapeseed pellets and wood pellets) in a low-power boiler. Such a comparison has not yet been encountered in the literature. As the paper proves, biomass can be used for energy purposes in a variety of ways, and the benefits vary greatly depending on the system used. Bioenergy systems can contribute to climate change mitigation, but the use of biomass resources requires careful consideration of how to target the actions taken in relation to available resources.

The engine test results showed significant reductions in CH_4 emissions when burning B100 biodiesel compared to burning conventional fuel, both at maximum torque and rated speed. Higher NO_x emissions were found for the biofuel burned relative to diesel combustion. In addition, higher CO_2 emissions expressed in $g \cdot kWh^{-1}$ were recorded for the combustion of bioester compared to the combustion of diesel, which is mainly due to an increase (about 10%) in the B100 fuel consumption, measured on the dynamometer bench. The engine test results showed a significant reduction in CH_4 emissions when burning B100 biodiesel compared to burning conventional fuel, both at maximum torque and rated speed. The boiler test results indicate that the combustion of rapeseed pellets is associated with higher CH_4 and NO_x emissions compared to the combustion of wood pellets. In contrast, comparable values were found for CO_2 emissions expressed in $g \cdot kWh^{-1}$ during the combustion of rapeseed and wood pellets.

Thus, the results obtained from the CO_2 emissivity studies do not clearly indicate the environmental benefits of using the two alternative fuels tested compared to their conventional counterparts. Neither in engine tests nor in boiler tests for NO_x emissions have any ecological benefits been shown from the use of alternative fuels. Only in the case of engine tests were significantly lower CH_4 emissions found when fueling the engine with methyl esters of rapeseed oil.

In conclusion, although the studies did not show significant environmental benefits of using rapeseed-derived fuels, they should not be disqualified. Further research into the combustion process of these fuels can help improve emission factors. In addition, the management of waste biomass such as rapeseed straw, thanks to the possibly longest retention of its economic value, will allow for the sustainable use of rapeseed crops and attempt to close the CO_2 cycle.

The agricultural sector is a sizable emitter of GHGs and a consumer of energy derived mainly from fossil sources. Hence, it is particularly important to use energy (in various forms) from renewable sources in agriculture as much as possible. The results of the authors' research can provide recommendations for the use of, for example, biomass-derived pellets or the more environmentally friendly biodiesel, given the significant amounts of fuel consumed by tractors and other agricultural vehicles. The authors intend to continue this type of research using various forms of agricultural biomass (e.g., biodiesel derived from frying oils) in terms of energy parameters, emissivity, combustion residues, etc.

The research results obtained in this paper are promising and indicate that biomass can play a key role in the diversification of raw material resources and sustainable management based on biotechnology. It is reasonable and interesting to conduct further research on the conversion to energy of different types of waste biomass in terms of greenhouse gas emissions, considering different energy systems. This will allow for an assessment of the environmental impact, selecting and popularizing the best solution.

Author Contributions: Conceptualization, J.W., G.Z., and J.S.-B.; methodology, J.W. and G.Z.; software, G.Z.; validation, A.K.; formal analysis, J.W.; investigation, J.W., G.Z., and J.S.-B.; resources, J.W. and G.Z.; data curation, G.Z.; writing—original draft preparation, J.W., G.Z., and J.S.-B.; writing—review and editing, A.K.; visualization, G.Z.; supervision, A.K.; project administration, G.Z.; funding acquisition, G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Beach, R.H.; Creason, J.; Ohrel, S.B.; Ragnauth, S.; Ogle, S.; Li, C.; Ingraham, P.; Salas, W. Global Mitigation Potential and Costs of Reducing Agricultural Non-CO_2 Greenhouse Gas Emissions through 2030. *J. Integr. Environ. Sci.* **2015**, *12*, 87–105. [CrossRef]
2. Hanaki, K.; Portugal-Pereira, J. The Effect of Biofuel Production on Greenhouse Gas Emission Reductions. In *Biofuels and sustainability*; Springer: Tokyo, Japan, 2018; pp. 53–71.
3. Oruc, O.; Dincer, I. Environmental Impact Assessment of Using Various Fuels in a Thermal Power Plant. *Int. J. Glob. Warm.* **2019**, *18*, 191–205. [CrossRef]
4. Cho, H.H.; Strezov, V. A Comparative Review on the Environmental Impacts of Combustion-Based Electricity Generation Technologies. *Energy Fuels* **2020**, *34*, 10486–10502. [CrossRef]
5. Jandacka, J.; Caban, J.; Nieoczym, A.; Holubcik, M.; Vrabel, J. Possibilities of Using Wood Waste for the Production of Fuel Briquettes. *Przem. Chem.* **2021**, *100*, 367–374. [CrossRef]
6. Hammar, T. *Climate Impacts of Woody Biomass Use for Heat and Power Production in Sweden*; Swedish University of Agricultural Sciences: Uppsala, Sweden, 2017; ISBN 978-91-576-8872-9.
7. Suhonen, H. *Novel Electrical Particle Emission Reduction Methods for Small-Scale Biomass Combustion*; Finnish Association for Aerosol Research: Helsinki, Finland, 2021; ISBN 978-952-7276-66-2.
8. Houghton, J.T.; Ding, Y.; Griggs, D.J.; Noguer, M.; van der Linden, P.J.; Dai, X.; Maskell, K.; Johnson, C.A. (Eds.) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2001; ISBN 0521 01495 6.
9. Estevez, R.; Aguado-Deblas, L.; López-Tenllado, F.J.; Luna, C.; Calero, J.; Romero, A.A.; Bautista, F.M.; Luna, D. Biodiesel Is Dead: Long Life to Advanced Biofuels—A Comprehensive Critical Review. *Energies* **2022**, *15*, 3173. [CrossRef]
10. Dzieniszewski, G.; Kuboń, M.; Pristavka, M.; Findura, P. Operating Parameters and Environmental Indicators of Diesel Engines Fed with Crop-Based Fuels. *Agric. Eng.* **2021**, *25*, 13–28. [CrossRef]
11. Lee, D.; Pomraning, E.; Rutland, C.J. LES Modeling of Diesel Engines. *SAE Trans.* **2002**, *11*, 2566–2578. [CrossRef]
12. Król, D.; Poskrobko, S.; Tokarz, Z.; Gościk, J.; Wasiak, A. The Fuel Biomass about Raised Caloricity. *Arch. Waste Manag. Environ. Prot.* **2017**, *19*, 11–16.
13. Juszczak, M. Evaluation of CO, NO, NO_x and Dust Concentration Values in Flue Gas from Thermal Conversion of Straw Ballots. *Arch. Gospod. Odpad. Ochr. Śr.* **2010**, *12*, 1–14.
14. Kachel, M.; Kraszkiewicz, A.; Subr, A.; Parafiniuk, S.; Przywara, A.; Koszel, M.; Zając, G. Impact of the Type of Fertilization and the Addition of Glycerol on the Quality of Spring Rape Straw Pellets. *Energies* **2020**, *13*, 819. [CrossRef]

15. Battaglia, M.; Thomason, W.; Fike, J.H.; Evanylo, G.K.; von Cossel, M.; Babur, E.; Iqbal, Y.; Diatta, A.A. The Broad Impacts of Corn Stover and Wheat Straw Removal for Biofuel Production on Crop Productivity, Soil Health and Greenhouse Gas Emissions: A Review. *GCB Bioenergy* **2021**, *13*, 45–57. [CrossRef]
16. Lorencowicz, E.; Uziak, J. Regional Structure of Tractor Market in Poland. *Agric. Eng.* **2020**, *24*, 51–62. [CrossRef]
17. Wasilewski, J.; Szyszlak-Bargłowicz, J.; Zając, G.; Szczepanik, M. Assessment of CO_2 Emission by Tractor Engine at Varied Control Settings of Fuel Unit. *Agric. Eng.* **2020**, *24*, 105–115. [CrossRef]
18. Wasilewski, J.; Krasowski, E. *Internal Combustion Engines*; Wydawnictwo Uniwersytetu Przyrodniczego: Lublin, Poland, 2015; ISBN 83-7259-238-1.
19. Demirbas, A. Combustion Characteristics of Different Biomass Fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230. [CrossRef]
20. Król, D.; Łach, J.; Poskrobko, S. O Niektórych Problemach Związanych z Wykorzystaniem Biomasy Nieleśnej w Energetyce. *Energetyka* **2010**, *1*, 53–62.
21. Juszczak, M. Concentrations of Carbon Monoxide and Nitrogen Oxides from a 15 KW Heating Boiler Supplied Periodically with a Mixture of Sunflower Husk and Wood Pellets. *Environ. Prot. Eng.* **2014**, *40*, 66–74. [CrossRef]
22. Zhao, W.; Li, Z.; Wang, D.; Zhu, Q.; Sun, R.; Meng, B.; Zhao, G. Combustion Characteristics of Different Parts of Corn Straw and NO Formation in a Fixed Bed. *Bioresour. Technol.* **2008**, *99*, 2956–2963. [CrossRef] [PubMed]
23. Houshfar, E.; Skreiberg, Ø.; Løvås, T.; Todorović, D.; Sørum, L. Effect of Excess Air Ratio and Temperature on NO_x Emission from Grate Combustion of Biomass in the Staged Air Combustion Scenario. *Energy Fuels* **2011**, *25*, 4643–4654. [CrossRef]
24. Li, Z. *Corn Straw and Biomass Blends: Combustion Characteristics and NO Formation*; Nova Science Publishers: New York, NY, USA, 2009; ISBN 1-61122-445-4.
25. Verma, V.K.; Bram, S.; Delattin, F.; Laha, P.; Vandendael, I.; Hubin, A.; De Ruyck, J. Agro-Pellets for Domestic Heating Boilers: Standard Laboratory and Real Life Performance. *Appl. Energy* **2012**, *90*, 17–23. [CrossRef]
26. Sarkan, B.; Kuranc, A.; Sejkorova, M.; Caban, J.; Loman, M. Comparison of the Exhaust Emissions of Heavy-Duty Vehicle Engines Powered by Diesel Fuel (DF) and Natural Gas (LNG) in Real Operation Conditions. *Przem. Chem.* **2022**, *101*, 37–41. [CrossRef]
27. Kuranc, A.; Słowik, T.; Krzaczek, P.; Maj, G. Emission of Fumes of Ursus MF235 under Conditions of Load with the Use of a Movable Dynamometric Stand. *Agric. Eng.* **2016**, *20*, 101–112. [CrossRef]
28. Maia, E.C.R.; Borsato, D.; Moreira, I.; Spacino, K.R.; Rodrigues, P.R.P.; Gallina, A.L. Study of the Biodiesel B100 Oxidative Stability in Mixture with Antioxidants. *Fuel Process. Technol.* **2011**, *92*, 1750–1755. [CrossRef]
29. Demirbas, A. Progress and Recent Trends in Biodiesel Fuels. *Energy Convers. Manag.* **2009**, *50*, 14–34. [CrossRef]
30. Arshad, M.; Zia, M.A.; Shah, F.A.; Ahmad, M. An Overview of Biofuel. In *Perspectives on Water Usage for Biofuels Production: Aquatic Contamination and Climate Change*; Arshad, M., Ed.; Springer International Publishing: Cham, Switzerland, 2018; pp. 1–37. ISBN 978-3-319-66408-8.
31. Kousoulidou, M.; Fontaras, G.; Ntziachristos, L.; Samaras, Z. Biodiesel Blend Effects on Common-Rail Diesel Combustion and Emissions. *Fuel* **2010**, *89*, 3442–3449. [CrossRef]
32. Zajac, G.; Wegrzyn, A. Analysis of Work Parameters Changes of Diesel Engine Powered with Diesel Fuel and FAEE Blends. *Eksploat. Niezawodn.-Maint. Reliab.* **2008**, *38*, 17–24.
33. Silitonga, A.S.; Hassan, M.H.; Ong, H.C.; Kusumo, F. Analysis of the Performance, Emission and Combustion Characteristics of a Turbocharged Diesel Engine Fuelled with Jatropha Curcas Biodiesel-Diesel Blends Using Kernel-Based Extreme Learning Machine. *Environ. Sci. Pollut. Res.* **2017**, *24*, 25383–25405. [CrossRef] [PubMed]
34. Nanaki, E.A.; Koroneos, C.J. Comparative LCA of the Use of Biodiesel, Diesel and Gasoline for Transportation. *J. Clean. Prod.* **2012**, *20*, 14–19. [CrossRef]
35. Fazio, S.; Monti, A. Life Cycle Assessment of Different Bioenergy Production Systems Including Perennial and Annual Crops. *Biomass Bioenergy* **2011**, *35*, 4868–4878. [CrossRef]
36. Thornley, P.; Gilbert, P.; Shackley, S.; Hammond, J. Maximizing the Greenhouse Gas Reductions from Biomass: The Role of Life Cycle Assessment. *Biomass Bioenergy* **2015**, *81*, 35–43. [CrossRef]
37. Bentsen, N.S.; Jack, M.W.; Felby, C.; Thorsen, B.J. Allocation of Biomass Resources for Minimising Energy System Greenhouse Gas Emissions. *Energy* **2014**, *69*, 506–515. [CrossRef]
38. Brack, D.; Hewitt, J.; Marchand, T.M. Woody Biomass for Power and Heat: Demand and Supply in Selected EU Member States; United Kingdom. 2018. Available online: https://policycommons.net/artifacts/613609/woody-biomass-for-power-and-heat/1593617/ (accessed on 15 September 2022).