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Combustion Efficiency of Various Forms of Solid Biofuels in Terms of Changes in the Method of Fuel Feeding into the Combustion Chamber

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Abstract: This study analyzes the combustion of pellets and briquettes made of plant biomass in low-power heating devices powered periodically with fuel being placed on the grate, as well as after modification using an automatic fuel feeding system in the gutter burner. The use of herbaceous biomass in the form of pellets in low-power heating devices with automatic fuel feeding and combustion in a gutter burner is not widely promoted and popular. Therefore, this study used four types of herbaceous waste biomass (wheat straw, rye straw, oat straw and hay) and one type of woody waste biomass (birch sawdust) for testing. The basic chemical characteristics were determined for the raw materials. After appropriate preparation, the selected starting materials were subjected to briquetting and pelleting processes. Selected physical properties were also determined for the obtained biofuels. Biofuels made from birch sawdust had the lowest heat value (16.34 MJ·kg^{-1}), although biofuels made from wheat, rye and hay straw had a slightly lower calorific value, respectively: 16.29; 16.28 and 16.26 MJ·kg^{-1}. However, the calorific value of oat straw biofuels was only 15.47 MJ kg^{-1}. Moreover, the ash content for herbaceous biomass was 2–4 times higher than for woody biomass. Similar differences between herbaceous and woody biomass were also observed for the nitrogen and sulfur content. To burn the prepared biofuels, a domestic grate-fired biomass boiler was used, periodically fed with portions of fuel in the form of pellets or briquettes (type A tests), which was then modified with a gutter burner enabling the automatic feeding of fuel in the form of pellets (type B tests). During the combustion tests with simultaneous timing, the concentration of CO_2, CO, NO and SO_2 in the exhaust gases was examined and the temperature of the supplied air and exhaust gases was measured. The stack loss (qA), combustion efficiency index (CEI) and toxicity index (TI) were also calculated. The research shows that the use of automatic fuel feeding stabilizes the combustion process. The combustion process is balanced between herbaceous and woody biomass biofuels. Disparities in CO_2, CO and T_{gas} emissions are decreasing. However, during type B tests, an increase in NO emissions is observed. At the same time, the research conducted indicates that the combustion of herbaceous biomass pellets with their automatic feeding into the combustion chamber is characterized by an increase in combustion efficiency, indicating that when the combustion process is automated, they are a good replacement for wood biofuels—both pellets and briquettes.

Keywords: pellets combustion; briquettes combustion; emission; combustion efficiency index (CEI); toxic index (TI)

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1. Introduction

Biomass is an abundant source of renewable energy. Its use in the world promotes significant environmental and socio-economic benefits. This is particularly visible through the use of residues of agricultural by-products and waste from the agri-food industry. Currently, efforts are being made to use these raw materials as effectively as possible, and a common trend is to recycle them by finding other ways of using them. Such actions are intended to help reduce the use of fossil fuels, which, together with improving the efficiency of their use, will help reduce CO_2 emissions [1–6]. Hence, the interest in using plant biomass for energy purposes is constantly growing, which is helped by the fact that it is one of the key solutions proposed by the European Commission to reduce dependence on imported fossil fuels and thus improve the security of energy supplies in the long run [7,8]. The interest in biomass and biofuels produced from it also results from the broader promotion of renewable energy sources, which is associated with the modernization of buildings to improve their energy efficiency, which is based on the optimization of the heat sources used in them. During this work, hybrid installations using various renewable energy sources are becoming popular. Such work is also intended to contribute to reducing the emission intensity of buildings [9].

Solid biofuels, especially those of wood origin, compared to fossil fuels, in addition to blocking the increase in greenhouse gas emissions, also help reduce emissions of sulfur and nitrogen oxides. Nevertheless, this aspect is very dependent on the combustion conditions, active regulation of the combustion process, combustion system and type of fuel (chemical composition) and shape, which is widely reported in the literature on the subject. Nevertheless, these research works largely pointed to the advantage of the properties of woody biofuels and their impact on the combustion process, to some extent depreciating herbaceous biomass [10–33].

Among the various thermochemical processes for the oxidation of biofuels, the available processes include combustion, pyrolysis, Fischer–Tropsch gasification/synthesis and biomass liquefaction [34–36]. The combustion of such diverse forms of biofuels takes place in a different way using various types of heating devices, including those based on grate systems and using automatic fuel feeding to the combustion chamber using retort or gutter burners. Regardless of the combustion technique used, the combustion process can be divided into three phases. The first phase is accompanied by excessive outgassing of moisture and volatile particles, which is accompanied by quite high emissions of CO and NO. The second phase involves flame combustion and significant emission reduction. The third phase is the afterburning of the char, which is also accompanied by slightly higher CO emissions [37]. Combustion, as a common thermal utilization of biomass, is also accompanied by the formation of fly ash. Emission problems are exacerbated by the content of N, Cl, S and heavy metals in the fuel. For example, high concentrations of heavy metals contaminate the ash, while increased Cl content may increase the risk of corrosion [38,39]. Moreover, the presence of K content negatively affects the melting properties of the ash and thus causes high aerosol formation and particle emissions [35]. The factor controlling the combustion of biomass pellets is the diffusion of mass and heat for the degassing stage, and chemical reactions for the char combustion stage [40].

When using solid biofuels in direct combustion processes, low chimney emissions (emissions from chimneys less than 40 m high) from household heating are important [41–43]. To counteract this, outdated boilers powered by solid fossil fuels are replaced with ecological energy sources. Pellet boilers are becoming more and more popular on the heating market. They mostly replace older generation multi-fuel boilers, which are very inefficient, especially when burning wood logs. A low-cost and quick improvement in energy efficiency and ecological energy production can be achieved by modernizing old grate-fired coal-fired boilers with the use of automatically dosing fuel-dosing burners powered by plant biofuels [44–48]. Pellets are mainly produced from the sawdust of coniferous or deciduous trees from debarked stems. This raw material provides the best possible quality given its high lignin content, which has a strong bond and high calorific value. However, in the pursuit of developing small-scale pellet production useful for maintaining the economy and energy independence of rural areas, it is important to find alternative raw materials, among agricultural residues defined as herbaceous biomass. These raw materials should be suitable for production without bonding additives, without energy consuming the pre-treatment of biomass and then enable the combustion process to obtain appropriate energy, the production of which will not pollute the atmosphere. Pellets made from herbaceous biomass should enable achieving the same quality standards in terms of physical and, if possible, chemical characteristics as pellets made from wood sawdust. The most common concerns when producing pellets from alternative raw materials are low bulk density and mechanical strength, but also ash content and, in some cases, the presence of nitrogen, sulfur and chlorine. Compared to non-densified biomass, pellets are characterized by lower moisture, higher calorific value, uniform shape, clear combustion and reduced ash [49–55]. Additionally, in some areas with mainly agricultural production, the presence of herbaceous biomass helps shorten the supply chain, which is consistent with the concept of sustainable development. This is important because these factors have an increasing impact on market output as well as individual consumer choice [56,57].

In such socio-ecological and technical realities, when the use of automatic burners powered by pellets increases, it is important to verify the combustion of herbaceous biomass pellets inside them. In the literature on the subject, given the analyzed state of technology, it is difficult to find information related to the emissivity and efficiency of the use of these biofuels made from herbaceous biomass, which was combusted on a grate and in a gutter burner and compared to woody biomass. Here, the effectiveness of this process is analyzed in two ways. Combustion energy efficiency is understood as an indicator reflecting the energy yield less the chimney loss in typical operating conditions. However, ecological efficiency is defined by obtaining the lowest possible combustion losses while reducing CO, NO and SO_2 emissions or the toxicity index (TI), which indicates how clean the combustion process in the boiler is as the CO/CO_2 ratio [58–60].

The aim of this work is to assess the energy and ecological efficiency in terms of changes in the combustion process and emissions of exhaust gases such as CO, NO and SO_2 in a heating device with a different design of the combustion chamber and fuel supply system using biofuels in the form of briquettes and pellets made from wood and herbaceous biomass.

2. Materials and Methods

2.1. Biofuels

Five raw plant materials were selected for testing. These were mostly herbaceous biomass such as wheat, rye, oat straw and meadow hay. Additionally, birch sawdust was also used for this study. The above-mentioned biomass is generally available in Poland in the Lublin Voivodeship as by-products of agricultural and forestry production. It is often used as solid biofuel in home or farm heating devices after processing into rectangular or cylindrical bales or pellets and briquettes. During the research, the obtained raw materials were processed into pellets and briquettes. Before the thickening process, each type was crushed in quantities of 100 kg in a standard hammer shredder using sieves with a hole diameter of 10 mm. The shredded material in each group of raw materials was divided into two parts, which were pelleted and briquetted. Before compaction, their moisture was measured using the dryer-weighing method in accordance with the EN ISO 18134-3:2015 standard [60]. In the thickening process, the optimal value of this parameter was assumed to be approximately 16–18% [61,62], and if necessary, the biomass was dried at room temperature or moistened with water. Pelletizing took place in a granulator with a flat matrix with a hole diameter of 8 mm and a thickness of 28 mm. Briquetting was carried out in a hydraulic briquetting machine with a thickening sleeve diameter of 50 mm. The technical parameters of these machines are presented in previous publications [14,63,64].

The moisture content of the produced biofuels was analyzed according to the same method as the moisture content in the raw materials. The carbon, hydrogen and nitrogen content was determined using an automatic analyzer according to the CEN/TS 15104:2006 method [65], and the sulfur content was determined using the PN-G-04584:2001 method [66]. Other technical parameters of the produced fuels, such as the content of volatile matter, ash and heat of combustion converted into calorific value, were determined using the following methods: PN-G-04516:1998 [67], EN ISO 18122:2016 [68], EN ISO 18125:2017 [69]. The density of the produced biofuels was determined based on measurements of the diameter (D) and length (L) of individual fuel granules, which were made directly with a caliper, according to the EN ISO 16127:2012 standard [70].

All the above-mentioned determinations and measurements were performed in working conditions, in three repetitions, and their values are presented in the tables.

2.2. Research Stand

In the first part of the research, the test stand used during the combustion tests of prepared pellets and briquettes consisted of a grate-type boiler with a nominal thermal power of 10 kW and an efficiency of 80%, whose rectangular combustion chamber with dimensions of 0.26 × 0.3 × 0.45 m was surrounded by a water jacket. Air was fed to the boiler at a speed of 1 $m \cdot s^{-1}$ under the grate using a controlled fan. The boiler was connected to a 3 m high chimney with an internal diameter of 130 mm.

However, in the second part of the research, a modernized test stand was used, in which the main additional element was an automatic gutter burner installed in the boiler door to the combustion chamber. It was a standard device in which the fuel is delivered from the store using a screw conveyor above the device, and then it is poured into the burner chamber, where the screw moves its portions towards the combustion zone, afterburning and the ash is poured onto the boiler grate. Above the combustion zone, in the combustion chamber, there is a ceramic plate that serves as a deflector. The installed burner allows the boiler to be fed with pellets or other biomass of similar granulation. Fuel ignition (via a built-in thermal igniter), fuel feeding time, blowing and downtime are regulated by an electronic controller.

Additionally, the test stand in two variants of operation was equipped with research equipment consisting of a liquid circulation pump, a flow meter, a pressure sensor and a water temperature measurement system (inlet and outlet) installed in the heating loop.

A diagram of the test stand detailing two combustion systems is shown in Figure 1.

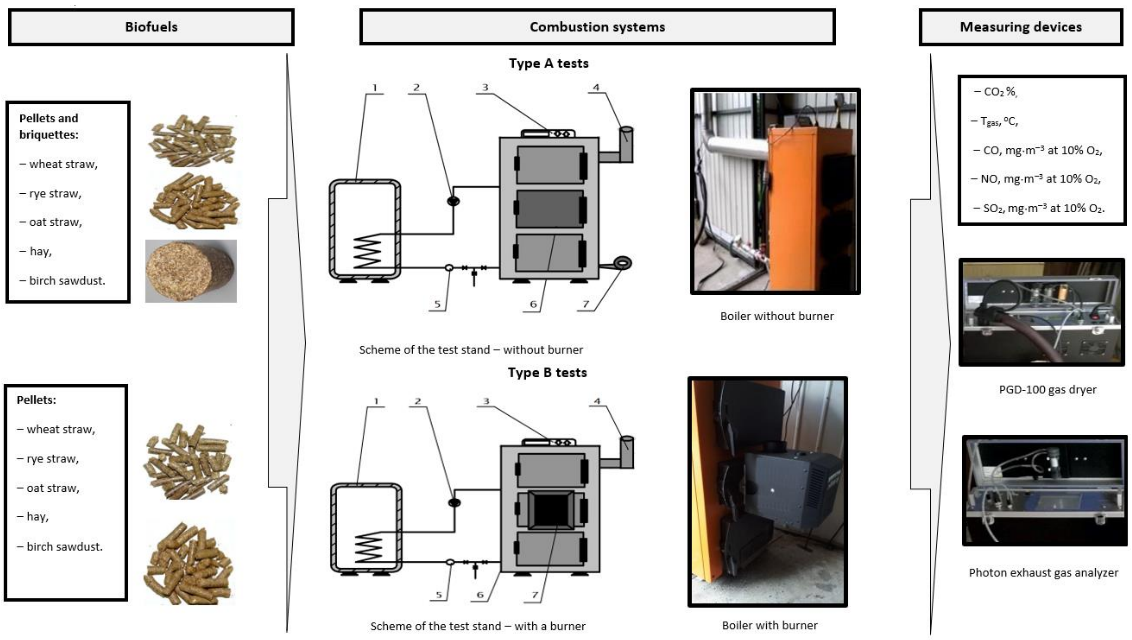

Figure 1. Diagram of measuring system: 1—heat exchanger, 2—pump, 3—microprocessor-based controller boiler, 4—chimney, 5—water flow rate meter, 6—boiler, 7—air fun (type A tests) or burner (type B tests).

2.3. Course of Combustion Tests

In the first part of the tests, the fuel collected for testing, the dimensions of which are given in Table 1, was burned periodically in fixed 1 kg portions. The process was carried out from the moment of ignition initiation by placing fuel on a stabilized layer of embers until the reaction quenched, which was assumed to be a drop in the exhaust gas temperature to 200 °C. This corresponded to stabilized conditions corresponding to everyday operation when refueling in these types of devices. Exhaust gases were collected from the chimney—Figure 1.

Table 1. Technical specifications of the gas analyzer equipment.

Gas	Measurement Range	Accuracy	Resolution	Type of Measurement
CO_2	0–25%	±3%	0.01%	NDIR
CO	0–2%	±0.0003%	0.0001%	NDIR
NO	0–0.5%	±0.0003%	0.0001%	NDIR
SO_2	0–0.5%	±0.0003%	0.0001%	NDIR
T_{gas}	$-10 \div 1000$ °C	±2 °C	0.1 °C	Type K thermocouple

In the second part of the tests, the boiler was fueled only with pellets. During this work, three stages of work were carried out, the first of which was the automatic ignition stage. At this stage, first the fan starts removing ash from the grate. Then, the initial dose of pellets is fed onto the grate and the electric igniter and blower fan are turned on. During this stage, the pellets heat up on the grate until a flame appears. This is signaled by the flame sensor. During this time of fuel ignition, the fan operates continuously, and fuel is periodically fed to the burner from the pellet hopper. In the burner, the fuel is moved to the combustion chamber using a screw conveyor.

When a flame appears, the boiler switches to nominal operation mode (the second stage of the operation analyzed). This period is associated with the increase in the temperature of the water in the jacket to reach the set temperature. During tests in this mode, the burner operated while burning 1 kg of a given type of fuel. The fuel feeding time was 8 s, the pellet feeding break was 10 s and the fan efficiency was 30%. After burning a portion of fuel, the measuring system was cooled and cleaned.

In both variants, the combustion process was timed, and the composition and temperature of the exhaust gases were measured and recorded throughout the combustion process. The measurement probe was connected to a flue gas dryer, from which the flue gases went to the flue gas analyzer. During the tests, a portable exhaust gas analyzer based on infrared (NDIR) sensors was used for the following gases: CO, CO_2, NO, SO_2. The temperature was measured using a K-type thermocouple located in the exhaust gas sampling probe. Detailed technical data of the analyzer are presented in Table 1.

The results recorded during the tests were sent from the analyzer to a PC computer, which was used to verify the distribution of the results obtained in a Microsoft EXCEL Professional Plus 2021 spreadsheet. Combustion phases were determined based on changes in CO and CO_2 emissions as reported in [17,71]: I—start of combustion characterized by flameless release of volatile parts of the fuel to the maximum CO content, II—basic combustion, which is manifested by the presence of a flame and rapid combustion of volatile parts to a minimum of CO in the exhaust gases, III—after-combustion of the fuel, which is characterized by the disappearance of the flame and burning of fuel residues in the ember layer and another increase in CO emissions. In each variant, three repeated measurements were made, detailing the phases for which the arithmetic mean was given.

The obtained results of the CO, NO and SO_2 concentrations in the exhaust gases were related to the dry exhaust gas volume flow with 10% oxygen content and standard conditions ($mg \cdot m^{-3}$) at 0 °C and 1013 mbar according to the guidelines contained in the PN-EN 303-5 standard: 2002 [72].

The combustion efficiency index was calculated using the formula [73,74]:

$$\mathrm{CEI} = 100 - q_A\ (\%) \tag{1}$$

where

qA—chimney loss calculated according to Formula (2) (%).

$$q_A = (T_{gas} - T_{amb}) \cdot \left(\frac{A_1}{CO_2} + B\right)\ (\%) \tag{2}$$

where

T_{gas}—exhaust gas temperature (°C);
T_{amb}—air temperature at the boiler inlet (ambient temperature) (°C);
CO_2—concentration of carbon dioxide in exhaust gases (%);
A_1, B—Siegert coefficients characteristic for biomass, $A_1 = 0.65$, $B = 0$.

The toxicity index was calculated based on formula 3 as the quotient of the concentration of carbon monoxide (CO) in the exhaust gases to the concentration of carbon dioxide CO_2 in the exhaust gases [58,60]:

$$\mathrm{TI} = \frac{CO}{CO_2} \cdot 100\ (\%) \tag{3}$$

where

CO—concentration of carbon monoxide in exhaust gases (%);
CO_2—concentration of carbon dioxide in exhaust gases (%).

All statistical analyses were conducted using the STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). The Shapiro–Wilk test checked the compliance of the results with the normal distribution, and the Brown–Forsythe test assessed the homogeneity of variances. Then, in individual phases, an analysis of variance was performed for factorial systems, where the grouping factors were the raw materials from which the agglomerates were made (wheat, rye, oat straw, meadow hay and wood sawdust), as well as the pellet and briquette grate combustion system (type A tests) and burning pellets in a gutter burner (type B tests). The Pearson correlation test was used to describe the relationship between individual variables. The observed differences were considered statistically significant at the significance level of $p < 0.05$.

3. Results

3.1. Results of Combustion Tests

Tables 2 and 3 present the physical and chemical characteristics of the biofuels used in the tests.

Table 2. Physical biofuels properties.

Fuel Type		L (mm)	D (mm)	MC (%)	VD ($kg \cdot m^{-3}$)
Wheat straw	P	32 ± 2^{a}	8 ± 0.25^{a}	10.60 ± 0.14^{a}	1130 ± 22
	B	16 ± 1^{b}	50 ± 1^{b}	10.40 ± 0.17^{c}	946 ± 24
Rye straw	P	29 ± 3	8 ± 0.25^{a}	10.40 ± 0.12^{b}	1034 ± 21^{a}
	B	19 ± 1^{b}	50 ± 1^{b}	10.30 ± 0.15^{c}	856 ± 20
Oat straw	P	34 ± 3^{a}	8 ± 0.25^{a}	10.50 ± 0.14^{ab}	1016 ± 20^{a}
	B	25 ± 2^{c}	50 ± 1^{b}	10.40 ± 0.13^{bc}	1004 ± 29^{b}
Hay	P	32 ± 2^{a}	8 ± 0.25^{a}	9.70 ± 0.19^{d}	1063 ± 21^{a}
	B	23 ± 2^{c}	50 ± 1^{b}	9.50 ± 0.16^{e}	1132 ± 33
Birch sawdust	P	11 ± 2	8 ± 0.25^{a}	9.80 ± 0.11^{d}	926 ± 18
	B	49 ± 3	50 ± 1^{b}	9.80 ± 0.12^{e}	996 ± 21^{b}

Acknowledgments: P—pellets, B—briquettes, L—length, D—diameter, MC—moisture content, VD—volatile density, ^{a,b,c,d,e} homogeneous group, ±standard deviation.

Table 3. Chemical biofuels properties plant raw materials.

Fuel Type	**C (% DM)**	**H (% DM)**	**N (% DM)**	**S (% DM)**	**VM (% DM)**	**LHV (MJ·kg^{-3})**	**AC (% DM)**
Wheat straw	47.03 ± 0.19 ^{a}	5.79 ± 0.07 ^{a}	0.78 ± 0.01 ^{a}	0.06 ± 0.02 ^{a}	70.70 ± 0.13 ^{b}	16.29 ± 0.10 ^{a}	2.8 ± 0.03
Rye straw	47.95 ± 0.21 ^{a}	5.92 ± 0.08 ^{b}	0.85 ± 0.01 ^{a}	0.12 ± 0.02 ^{a}	72.20 ± 0.12 ^{a}	16.28 ± 0.12 ^{b}	3.2 ± 0.04
Oat straw	43.70 ± 0.12	5.22 ± 0.04	1.04 ± 0.01	0.07 ± 0.02 ^{a}	69.50 ± 0.10 ^{b}	15.47 ± 0.8	6.5 ± 0.06 ^{a}
Hay	46.10 ± 0.13 ^{a}	5.85 ± 0.06 ^{a}	1.4 ± 0.01	0.61 ± 0.08	68.20 ± 0.09 ^{b}	16.26 ± 0.12 ^{b}	6.2 ± 0.05 ^{a}
Birch sawdust	49.10 ± 0.18	5.95 ± 0.05 ^{b}	0.22 ± 0.01	0.1 ± 0.01	73.40 ± 0.11 ^{a}	16.34 ± 0.11 ^{a}	1.3 ± 0.02

Acknowledgments: C—carbon, H—hydrogen, N—nitrogen, S—sulfur, VM—volatile matter, LHV—low heat value, AC—ash content, ^{a,b} homogeneous group, ±standard deviation.

The geometric dimensions of herbaceous biomass pellets are similar. Their diameter was 8 mm and the length ranged from almost 30 mm to almost 35 mm. Only the wood biomass pellets were approximately 50–60% shorter. The diameter of the briquettes was 50 mm, and their length was usually in the range of 15–25 mm (herbaceous biomass). The length of the wood biomass briquettes was twice as long. Other physical characteristics such as the moisture content and density were equal. The moisture content of the biofuels prepared for testing ranged from less than 10 to less than 11%, and the density ranged from 900 to 1132 kg·m^{-3}—Table 2. Much greater diversity of the produced biofuels resulted mainly from the individual chemical characteristics of the raw materials used, which are presented in Table 3.

The content of carbon and hydrogen volatiles varied slightly, with the maximum values for biofuels from wood biomass, rye straw and wheat straw. However, the nitrogen content was the lowest for biofuels from wood biomass and the highest for biofuels from hay, which also contained the most sulfur. The elemental composition means that the variability in the calorific value also corresponded to the maximum values of this parameter for biofuels from wood biomass, rye and wheat straw. At the same time, woody biomass had the lowest ash content, approximately 2–5 times lower than herbaceous biomass. It is also worth noting that oat straw and hay have twice the ash content than that determined for wheat and rye straw (Table 3).

The main idea resulting from the purpose of this study was to compare the combustion process in two types of heating devices: a device in which combustion took place periodically on the grate with air being fed under the grate and in the other one, where automatic feeding to the drop-in burner was used. In the first variant, pellets and briquettes were burned, while the second variant allowed burning only pellets. Only the second combustion phase was analyzed, without taking into account the different phases of ignition (I) and fuel afterburning (III). During combustion on a grate, the second combustion phase for the considered pellets lasted on average 140–150 s, and for briquettes, 150–180 s. However, combustion in a gutter burner for the pellets selected for testing lasted on average 600 s.

During the tests, the fuels burned completely without any disruption to the process. However, for biofuels made of oat straw and hay when burned on a grate, the formation of ash cakes was observed. When these biofuels were burned in a gutter burner, no such agglomerates were found—although the ash did not scatter. Figure 2 shows examples of the observed sinters.

Figure 3 shows the combustion temperatures of the considered biofuels under the test conditions. The average exhaust gas temperature was in the range of 270–420 °C. Only during type A tests using wood biomass pellets was the temperature much higher and amounted to 570 °C, and for oat straw and hay briquettes, it was much lower, being 150 and 200 °C.

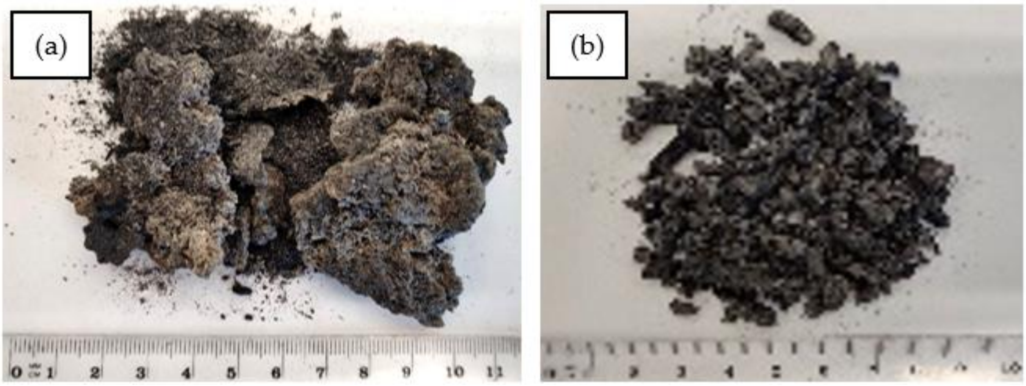

Figure 2. Bottom ash with the resulting sinters: (**a**) during type A tests, (**b**) during type B tests.

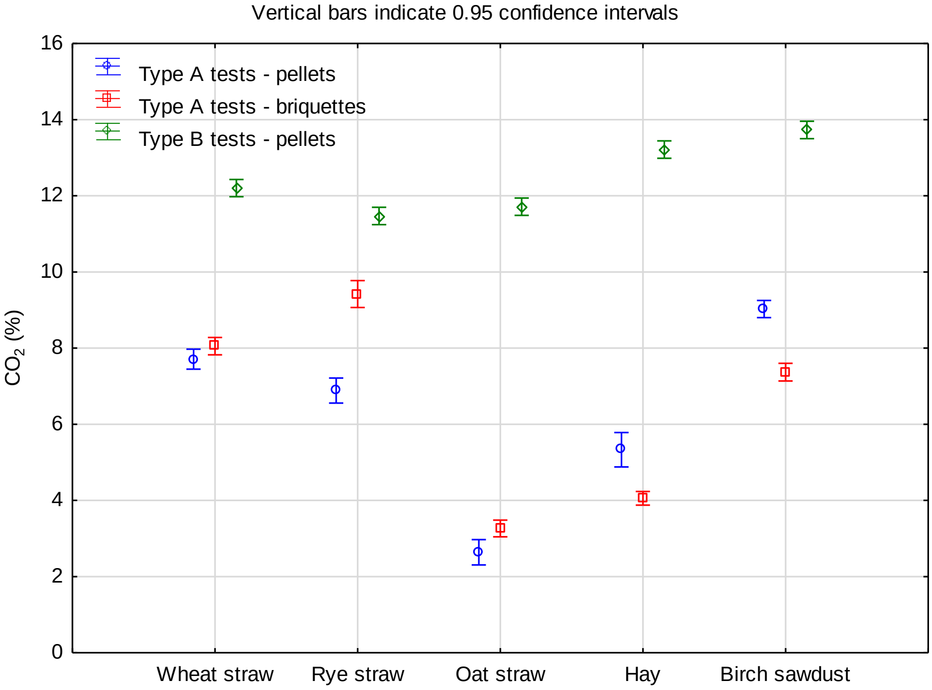

Figure 3. Content CO_2 in exhaust gases.

Figure 3 shows the CO_2 content in the exhaust gases. During the type A combustion tests, the CO_2 content when feeding the boiler, periodically placing fuel on the grate for pellets and briquettes made of wheat straw, rye straw and birch sawdust, ranged from 7–9%. However, under these test conditions, the combustion of pellets and briquettes made of oat straw and hay was characterized by much lower CO_2 emissions, approximately 3 and 5%, respectively, which indicated a lower combustion intensity of these fuels under the adopted test conditions. Changing the feeding system to the boiler during the type B tests resulted in an increase in combustion intensity while smoothing its course. The CO_2 content in these conditions was within a narrow range from less than 12 to less than 14%—Figure 3.

At the same time, the stability of the combustion process during the type B tests was also observed in the range of the exhaust gas temperature (T_{gas}). In most type A and B tests, the values of this parameter ranged from less than 300 to just over 400 °C. Only for the type A tests, for oats and hay, were the values much lower, at the level of 150–200 °C, and for wood sawdust pellets, the value was much higher—570 °C.

The detailed distribution of these parameters is shown in Figure 4.

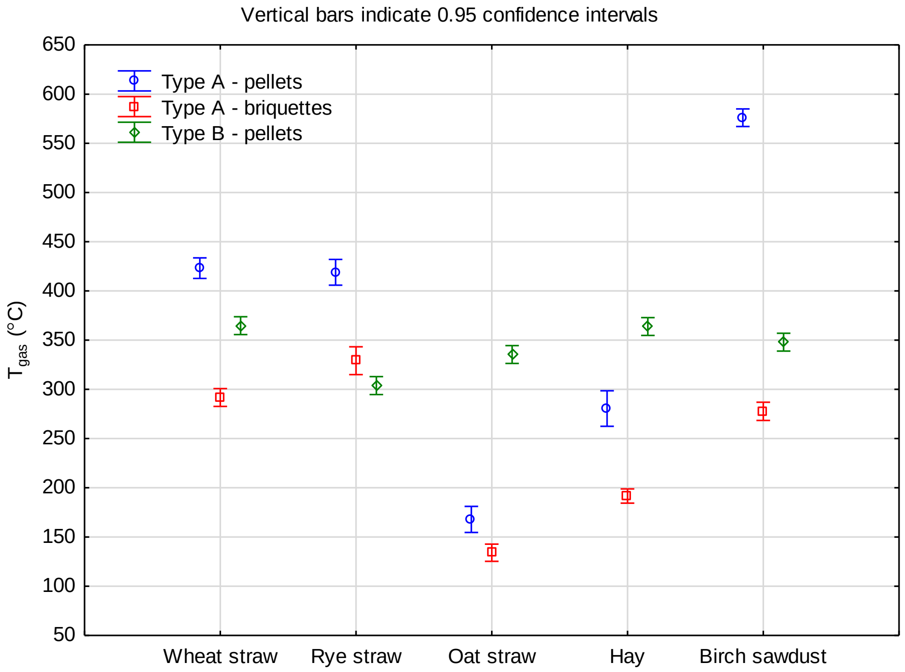

Figure 4. Temperature exhaust gases.

The recorded emissions of exhaust gas components such as CO, NO and SO_2 are, respectively, presented in Figures 5–7.

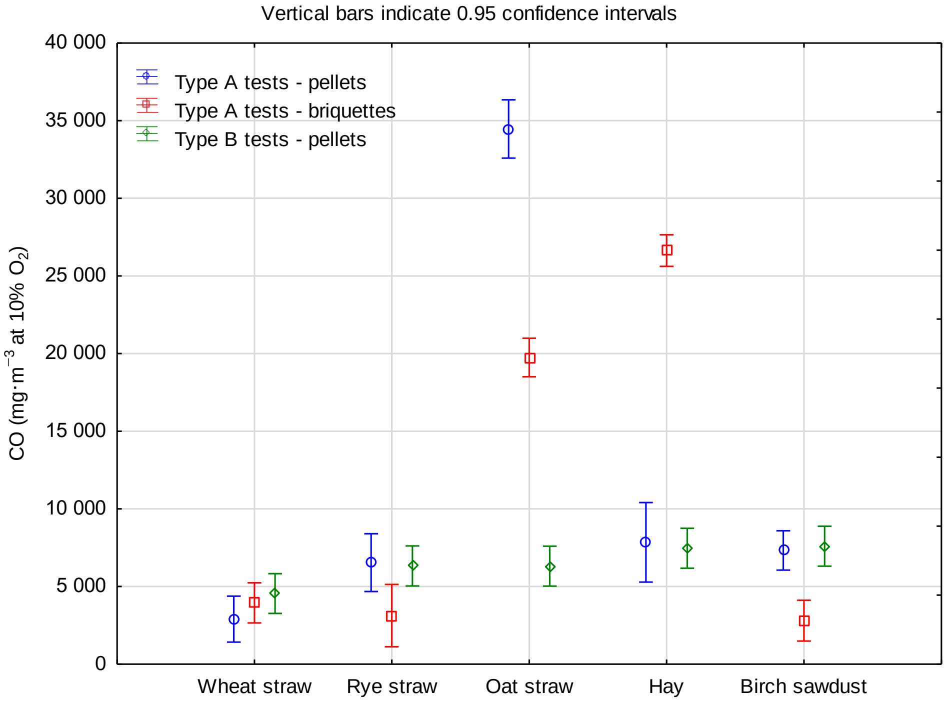

Figure 5. Exhaust gas emissions CO.

During the combustion tests, the carbon monoxide emissions were highest for pellets and briquettes made of oat straw and hay, which were burned on a grate. Compensated emissions, slightly lower than the highest one, were recorded for pellets burned in a burner. Nevertheless, the lowest emissions were recorded for pellets and briquettes made of wheat, rye and wood straw. These results indicate the diversified combustion of solid biofuels on the grate. Automatic fuel feeding and combustion in smaller portions make the combustion process more stable. As a rule, CO emissions were comparable to those observed for pellets burned on a grate—Figure 5.

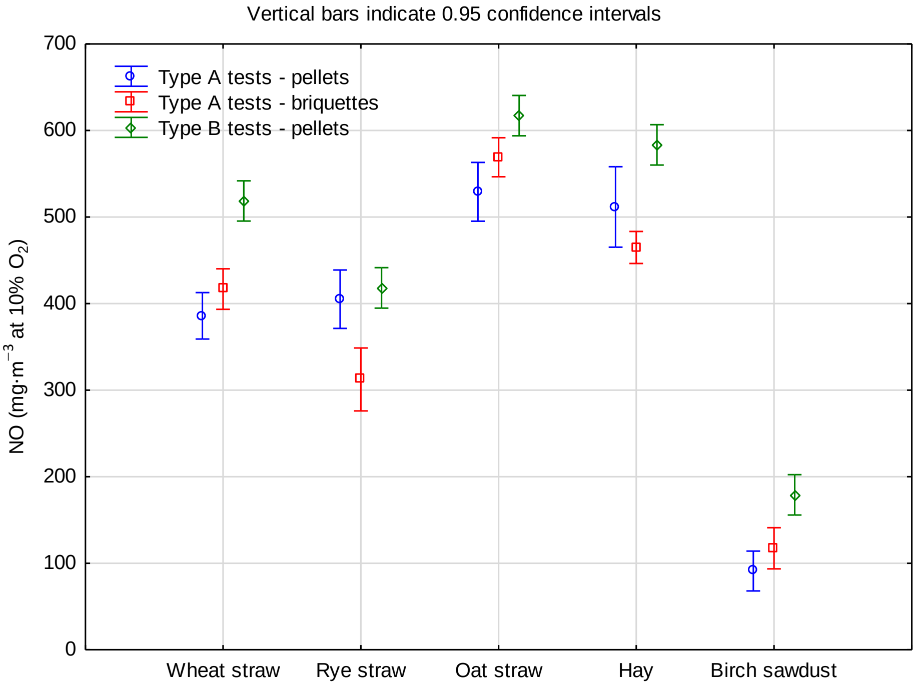

Figure 6. Exhaust gas emissions NO.

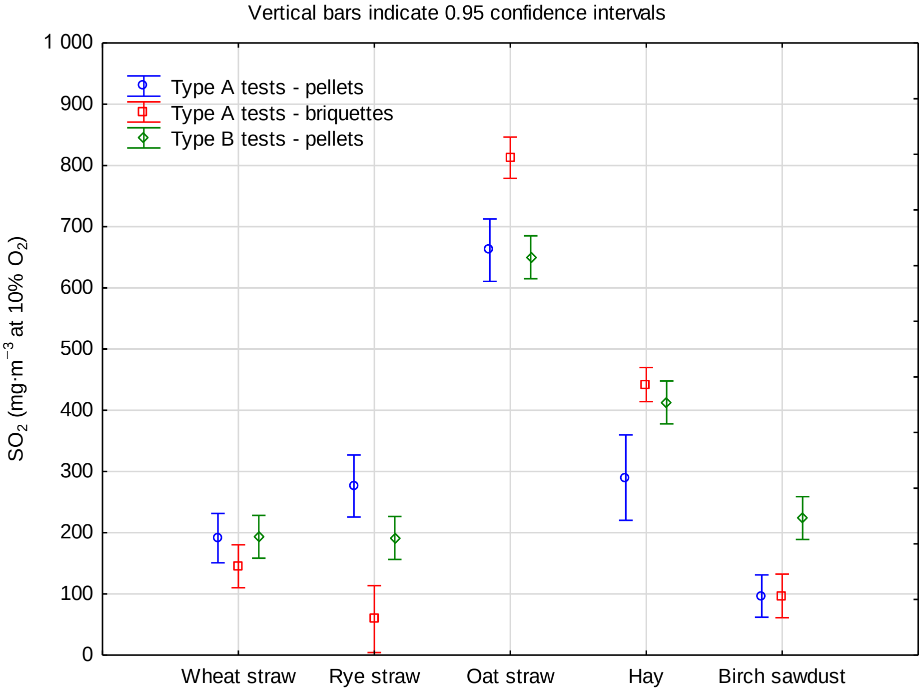

Figure 7. Exhaust gas emissions SO_2.

The use of modifications to the combustion process indicates slightly higher NO emissions when using all fuels. The highest values in the range of 480–620 mg·m^{-3} at 10% O_2 were observed for biofuels made from oat straw and hay. However, the lowest values of 100–180 mg·m^{-3} at 10% O_2 were observed for wood biomass—Figure 6.

Significant differences in SO_2 emissions were also observed during the tests. However, modernization did not lead to an increase in emissions of this compound. The trends in this case were ambiguous. At the same time, 2–3 times higher SO_2 emissions were observed during the combustion of biofuels made of oat straw and hay. Minimum values from almost 100 to 200 $mg \cdot m^{-3}$ at 10% O_2 were observed for biofuels from wheat straw, rye straw and wood sawdust—Figure 7.

The combustion efficiency and toxicity index are shown in Figures 8 and 9.

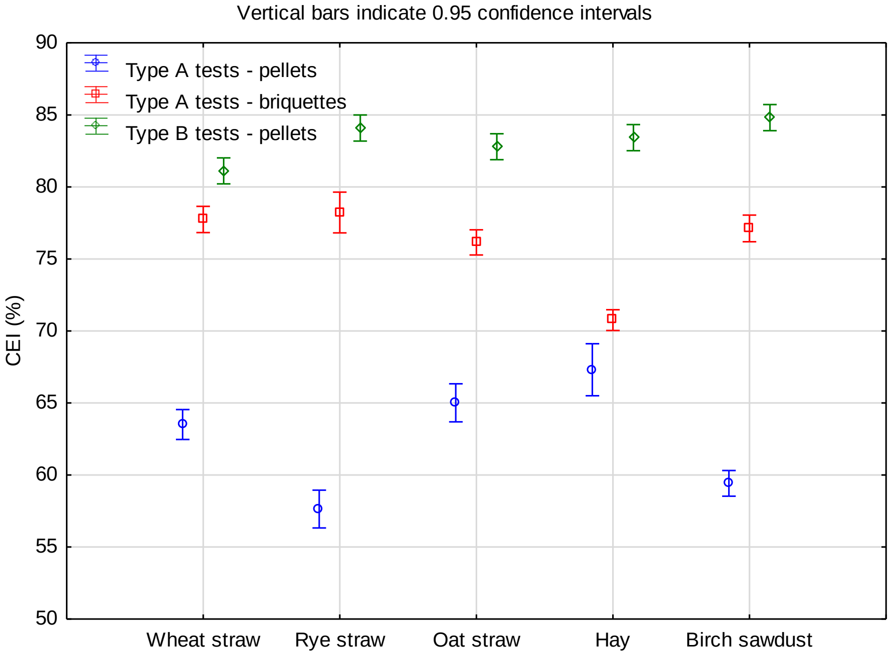

Figure 8. Combustion efficiency index (CEI).

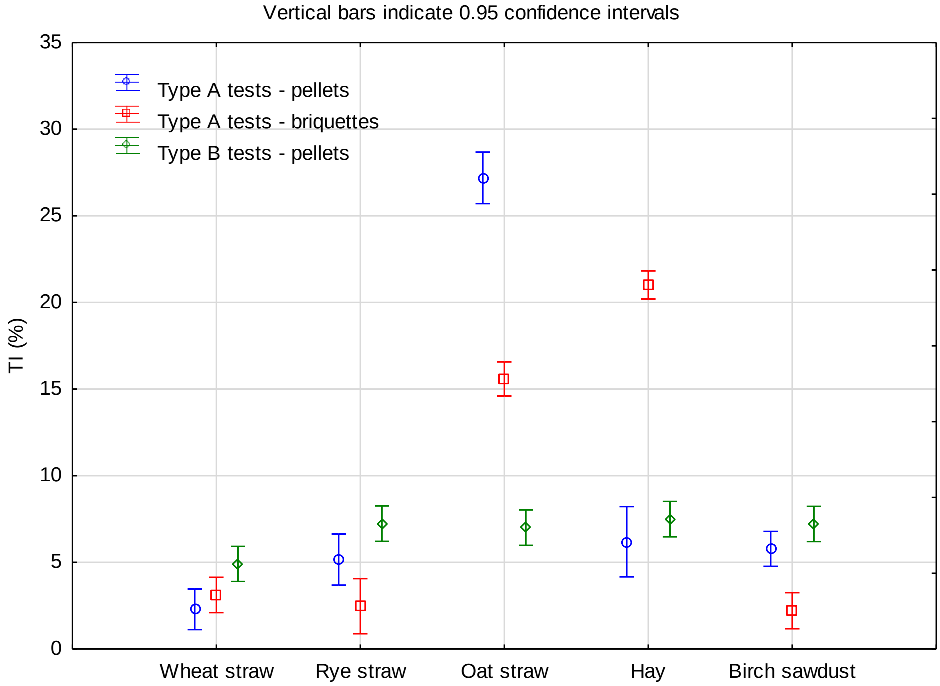

Figure 9. Toxic index (TI).

The combustion efficiency index indicates significant losses of energy generated when burning pellets on the grate. However, the most favorable and highest values of this indicator were observed for the combustion of pellets after the modernization of the heating device—Figure 8. The toxicity indicator indicated significant values for biofuels made of oat straw and hay, which were burned on a grate—Figure 9.

3.2. Statistical Analysis

The obtained results of the ANOVA are presented in Table 4. However, the Pearson correlation analyses for individual types of combustion tests are presented in Table 5.

Table 4. Analysis of variance (ANOVA)—*p* values for the studied characteristics.

Source of Variation	CO_2	T_{gas}	CO	NO	SO_2	CEI	TI
Combustion system (A)	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *
Raw material (B)	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	0.062 *	<0.001 *
AxB	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *

* significant values ($p < 0.05$).

Table 5. The pellets periodically on the grate.

Variable	C	H	N	S	AC	VM
Type A tests—pellets						
CO_2	0.677976 *	0.637564 *	−0.219322 *	−0.131930 *	−0.683694 *	0.563636 *
T_{gas}	0.784252 *	0.691406 *	−0.373775 *	−0.190893 *	−0.770876 *	0.712561 *
CO	−0.535296 *	−0.625937 *	−0.159288 *	−0.070670	0.502997 *	−0.242398 *
SO_2	−0.437705 *	−0.439179 *	0.074895	0.005168	0.421543 *	−0.326488 *
NO	−0.676691 *	−0.514921 *	0.559072 *	0.209989 *	0.671646 *	−0.765974 *
ETA	−0.205695 *	−0.163121 *	0.123506 *	0.112864 *	0.176628 *	−0.175854 *
TI	−0.535296 *	−0.625937 *	−0.159288 *	−0.070670	0.502997 *	−0.242398 *
Type A tests—briquettes						
CO_2	0.704775 *	0.531746 *	−0.266715 *	−0.436114 *	−0.786516 *	0.582540 *
T_{gas}	0.755073 *	0.642733 *	−0.143999 *	−0.287466 *	−0.760336 *	0.526193 *
CO	−0.503476 *	−0.236352 *	0.493940 *	0.579559 *	0.694502 *	−0.642508 *
SO_2	−0.789505 *	−0.722777 *	0.063510	0.132091 *	0.719139 *	−0.496293 *
NO	−0.888629 *	−0.665044 *	0.412040 *	0.232889 *	0.794973 *	−0.796485 *
ETA	0.219691 *	−0.107794 *	−0.632048 *	−0.749744 *	−0.535014 *	0.573628 *
TI	−0.503476 *	−0.236352 *	0.493940 *	0.579559 *	0.694502 *	−0.642508 *
Type B tests—pellets						
CO_2	0.287556 *	0.305380 *	−0.021475	0.281295 *	−0.186012 *	0.248697 *
T_{gas}	−0.075365 *	0.035404	0.172279 *	0.297782 *	0.000149	−0.043886
CO	0.148532 *	0.170481 *	0.008111	0.423918 *	0.152757 *	0.059172
SO_2	−0.253245 *	−0.257952 *	0.053194	−0.139660 *	0.285812 *	−0.281442 *
NO	−0.221545 *	−0.264598 *	−0.011205	−0.312259 *	0.193595 *	−0.230791 *
ETA	0.367725 *	0.291042 *	−0.171742 *	0.122989 *	−0.109338 *	0.276779 *
TI	−0.005151	0.020863	0.052841	0.297141 *	0.261704 *	−0.097229 *

* marked correlation coefficients are significant with $p < 0.05$.

The statistical analysis showed significant differences between the average values of all the analyzed exhaust gas parameters, except combustion efficiency in terms of the plant material grouping factor ($p = 0.062$). However, post-hoc Tukey tests indicated statistically significant differences in the average CO emission during the combustion of pellets and oat straw briquettes and hay briquettes on the grate in the analyzed three forms of combustion (type A tests—pellets, type A tests—briquettes and type B tests—pellets). For NO emissions, post-hoc tests in the two adopted combustion systems (type A and B tests) did not reveal homogeneous groups in terms of pellet combustion. And in terms of SO_2 emissions, these tests showed the lack of homogeneous groups between the SO_2 content in the exhaust gases generated when burning pellets and briquettes on the grate and pellets in the gutter burner.

4. Discussion

The chemical composition of the biofuels used during the tests had a similar impact on the combustion process and emission components when burning pellets and briquettes on a grate. The combustion of pellets in a trough burner with its automatic feeding into the combustion chamber resulted in a weakening of the connections with the components of exhaust gases, which is particularly important in the formation of NO and SO_2 from nitrogen and sulfur contained in the fuel. Additionally, in this combustion system (type B tests), higher fuel carbonization did not indicate an increase in the CO_2 content and exhaust gas temperature, which would indicate better combustion dynamics. The ash content in the analyzed fuels during the type A tests had quite strong negative relationships with CO_2 and T_{gas}, as well as slightly weaker positive relationships with CO, NO and SO_2 emissions. However, during combustion during the type B tests, these relationships weakened and were not so clear. It is also worth noting that the volatile matter content on combustion intensity and emission for all tests had opposite relationships than those with the ash content (Table 5).

The biofuels in the form of pellets and briquettes used during the research mostly belonged to the group of biofuels made from herbaceous biomass. Additionally, wood biomass fuel was also used for the tests (a representative of a popular fuel, eagerly used by consumers, characterized by favorable combustion and emission characteristics), whose task under the test conditions was to determine the desired reference point for the analyzed features. In terms of chemical characteristics, the collected raw materials were characterized by significant differences not only between herbaceous and woody biomass but also within herbaceous biomass. These differences were not only related to the energy concentration in the fuel (expressed by C, H, AC and LHV) but also to the presence of features affecting emissions (N, S, VM). However, within the biomass species, the mentioned features did not differ from those presented in the literature [26,75–79].

The work carried out related to the processing of collected raw materials into briquettes and pellets resulted primarily in equalizing the moisture content of these biofuels to a level of approximately 10% and increasing the density on average to approximately 900–1100 $kg \cdot m^{-3}$. The diameters for briquettes and pellets were equal, 50 and 8 mm, respectively. Differences in physical characteristics were observed in the length, which for briquettes made of herbaceous biomass was usually in the range of 20–30 mm, and those made of wood biomass were 50 mm long. However, for pellets, this parameter was even three times higher for granules made of herbaceous biomass. All 10 types of analyzed biofuels (5 pellets and 5 briquettes) met the requirements of the EN-ISO-17225 standard [80] in terms of geometric features, which are given in individual parts of this standard 2, 3, 6 and 7 relating to pellets, wood briquettes and non-woody pellets and briquettes, respectively.

The combustion processes carried out periodically with fuel on the grate (type A tests) and with automatic fuel feeding into the combustion chamber using a gutter burner (type B tests) are fundamentally different. By deciding to analyze only phase II of combustion, which did not include fuel ignition and afterburning, attempts were made to take into account the most reliable test conditions. The recorded combustion parameters, such as combustion time, CO_2 content in the exhaust gases and exhaust gas temperature, were within a fairly wide range of values of these parameters available in the literature for other heating devices. It is worth noting here that during the tests, the parameters were recorded at full heat demand from the boiler [26,29,81].

In the case of carbon monoxide emissions during the type B tests, lower emissions were observed than for pellets during the type A tests. It is important that the range of emissions between individual raw materials has been limited. This is due to the limitation of the amount of fuel burned at a given time in the burner, which often limits random zones of combustion and fuel ignition occurring on the grate, which result from the incomplete distribution of high temperature and the movement of air through the bed. This results in the formation of zones of incomplete combustion on the grate, which leads to the production of CO [82]. This is also related to the diversity of emissions when burning biofuels on a grate. It is worth noting that in the case of both the type A and B tests, the carbon monoxide emissions when burning biofuels from herbaceous and woody biomass did not meet the most stringent requirements specified in the PN-EN 303-5:2012 standard. Nevertheless, the wheat straw biofuels burned with CO emissions below 500 $mg \cdot m^{-3}$. Rye and birch sawdust briquettes also burned below this value, the standard for class 3 stoker boilers fed periodically.

In the test conditions for biofuels from herbaceous biomass, significant differences were observed, and the increased NO emission values were several times higher than the normative values given in the EcoDesign directive [83]. Such abnormal emissions were not observed during the combustion of wood biofuels. It is believed that this is mainly determined by the increased content of nitrogen (N) in the herbaceous biomass, which is responsible for the formation of NO in exhaust gases [2,84–89]. Nevertheless, in our own research, the change in the combustion system led to an increase in NO emissions for all types of raw materials, which could result from a higher temperature in the combustion chamber, as evidenced by a higher temperature of exhaust gases—Figure 3. According to Lamberg [90], thermal oxidation of nitrogen from atmosphere in biomass boilers is on a small scale and does not play a significant role due to the relatively low combustion temperatures (below 1300 °C)—however, under specific conditions, in a short time, it may occur. This is confirmed by research by Połczyńska and Juszczak [91] indicating an increase in NO emissions with the increasing temperature. Additionally, Mentes et al. [92] report that regardless of the type of boiler, there is a clear linear relationship between the amount of CO_2 and NO_x. At the same time, some authors of other studies reported higher NO_x emission values for the flame phase (II) in relation to the ignition (I) and after-combustion phase (III) [93,94]. These observations were confirmed by the consistency of the presence of nitrogen in the fuel and the mechanisms of its release during after-combustion, where the dominant feature is the conversion of char-N [2] with lower NO_x formation in relation to the conversion path of volatile nitrogen fractions. Nevertheless, the positive correlation with nitrogen content is not dominant in the context of its release from biomass [95]. As noted in our own previous research (14), under the conditions of these studies, two paths of NO formation from fuel nitrogen were observed, which partly goes to the volatile parts and partly remains bound in the fuel. And what is important in type A tests, when testing two forms of biofuels (pellets and briquettes), is the distribution of air through such deposits, its availability and the time of movement through the deposit. However, in type B systems, with an increase in the combustion intensity, combustion temperature and CO_2 emissions, the NO emission is determined by conditions in the combustion chamber other than the nitrogen content in the fuel. Additionally, the occurrence of increased NO emissions corresponds to SO_x emissions [96]. In terms of SO_x emissions, it should be clearly noted that the combustion of biofuels is associated with a significant reduction compared to coal fuels [47,97–101]. When burning fuels with sulfur, the sulfur from the fuel usually remains in the ash. Garcia-Maraver and Carpio [102] indicate that in the case of cereal straw combustion, the ash may contain from 40 to 55% of fuel sulfur. The remaining part of fuel sulfur in exhaust gases occurs mainly in the form of SO_2. However, some SO_3 can be formed at lower temperatures when more oxygen is bonded to the sulfur. Problems related to sulfur emissions should be expected at fuel concentrations above 0.2 weight [29,30,102–104]. During the combustion of herbaceous and woody biofuels in type A tests, lower SO_2 emissions were generally observed than when burning pellets in a gutter burner. Additionally, higher emissions were recorded for biofuels from oat straw and hay. However, under the test conditions, no strong unambiguous relationships were found between the sulfur content in the fuel (Table 5). In previous preliminary studies [105], periodic, batch burning of wheat straw and hay briquettes on a grate indicated significant SO_2 emissions associated with changes in the temperature in the combustion chamber. Qi et al. [96] indicate that the process of SO_2 formation from biomass during its combustion is not obvious and is related to many factors, including the following: sulfur content in biomass, combustion temperature and reactive elements that may react with sulfur. Krzywanski et al. [106] indicate that the inhibition of CO oxidation occurs in the presence of high SO_2 concentrations, and the increase in the conversion of carbon to CO in the presence of SO_2 also reduces NO emissions. However, as Yilgin et al. point out [107], SO_2 emissions arise during the combustion of volatile substances and increase with the rising temperature.

However, at a temperature of 800 °C, due to the ability of calcined carbonate minerals to bind sulfur dioxide, it may be reduced. Also, Lupiáñez et al. [108] indicate that the high content of alkali metals in biomass may reduce SO_2 emissions. Also, Mitchell et al. [2] notice the capture of these gases in situ by natural material, calcium salts in inorganic material.

During tests for biofuels produced from herbaceous biomass burned on a grate, the formation of sinter and slag was observed. Generally, for the analyzed biomass, the risk of sintering and ash deposition on the structural elements of heating devices concerns oat straw and hay, decreasing for wheat and rye straw and practically non-existent for wood biomass [109,110]. It is important that this coincides with the highest ash content for oat straw and hay and its impact, as stated by Choiński [59] after Vicente [111], on the reduction in combustion efficiency and the increase in CO, NO and SO_2 emissions.

In the test conditions, when assessing the combustion process in relation to the combustion system used, attention was paid to the change in combustion efficiency using boiler modifications during the type B tests. The increase in this efficiency and stability when using various fuels indicates a positive aspect of such modernization. However, the range of these values of 80–85% was lower than those reported in the literature, often reaching over 90% [89]. However, this parameter depends on the burner design and operating settings. However, the exhaust gas toxicity index taking into account CO emissions in relation to the CO_2 content in the exhaust gases indicates that the modification of the combustion chamber eliminates the differences between fuels but does not significantly reduce the value of this index. As indicated by the research of Anca-Couce [58], this relationship increases with the increase in the combustion temperature to 1000 °C, and then decreases due to the oxidation of CO taking place in the gas phase. At temperatures typical for biomass combustion, the recorded values of this indicator were 10 times lower than for biomass, which were given in the work by Anca-Couce [58].

5. Conclusions

During the research, fuels were used in the form of briquettes and pellets, which were made from herbaceous biomass such as wheat straw, rye straw, oat straw and hay and from wood biomass—birch sawdust. These biofuels were burned in two types of tests, which differed in the modification of the combustion and fuel feeding systems. Type A tests used a combustion chamber with air fed under a grate to which fuel—briquettes or pellets—was periodically fed. However, in the type B tests, the boiler was modified by installing a drop-in burner automatically fed with pellets in the door of the combustion chamber. The combustion process was analyzed in terms of its course, describing CO_2 emissions and the temperature of exhaust gases (T_{gas}) and in terms of emissivity in terms of the content of CO, NO and SO_2 in the exhaust gases. The technical solutions used and their energy production using biofuels from herbaceous and woody biomass were compared in terms of the combustion efficiency (CEI) and toxicity index (TI). The test results indicate that briquettes, not pellets, should be burned on the grate. A burner should be used to burn pellets. The use of a burner and automatic fuel feeding to the boiler, compared to wood pellets, helps stabilize the combustion process of biofuels from herbaceous biomass, which is confirmed by reduced combustion losses, increased efficiency and reduced toxicity index. Such a modification, significantly affecting the efficiency of the combustion process, can reduce energy losses and costs incurred by users. Stabilization of the combustion process of herbaceous biomass diversified in terms of chemical characteristics should increase the use of waste biofuels, while promoting decarbonization and achieving climate neutrality as quickly as possible. Adaptation of old boilers through the use of modern, ecological heating devices and biofuels is becoming an increasingly interesting alternative in the context of reducing the problem of air pollution caused mainly by the domestic and municipal sector, which uses outdated designs of coal-fired boilers, often powered by low-quality coal. While there is discussion about limiting the use of woody biomass from forests for energy purposes and attention is paid to increasing the use of herbaceous biomass from agriculture, these research results constitute new knowledge that facilitates decision-making when choosing a technique and biofuel. On a social level, this is still a topical topic. Nevertheless, critically approaching these results, problems related to the use of herbaceous biomass related to the content of N, S and sinterable mineral fractions, which determine the course of combustion and the emissivity of this process, require further research. It would be advisable to verify the relationship not only between CO_2, CO, NO and SO_2 contained in the exhaust gases, but also the temperature in the combustion chamber, in relation to the occurrence of conditions favoring the formation of these compounds or their reduction, depending on the content of alkalis, carbonates and other mineral fractions in the biofuels, also in the context of preventing ash sintering.

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