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The Use of Bread Bakery Waste as a Binder Additive in the Production of Fuel Pellets from Straw

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Abstract: The paper presents the results of a study on the effects of the addition of bread bakery waste (stale bread, sometimes infected with mold, from store returns) to agricultural waste consisting of triticale straw on the process of solid biofuel pelleting and the physical and fuel properties of the obtained pellets. The pelleting process was conducted in a pelletizer equipped with a flat matrix, with holes 6 mm in diameter, and two pelleting rollers (for straw alone and for a mixture of straw and bread waste with mass fractions of 5, 10, and 15%). The addition of bread waste during the process of pelleting resulted in reduced power demand for the pelletizer in each of the analyzed cases. The largest decrease in the power demand (by approximately 18%, i.e., from 1.27 to 1.04 kW) was recorded for a 15% addition of sunflower seed bread to the mixture with straw. Moreover, the addition of bread waste also caused a significant increase in the kinetic strength of pellets compared to pellets produced from straw alone. The highest kinetic strength was obtained in the case of pellets produced from a mixture of straw with a 15% white bread content, i.e., 99.43%. For all of the analyzed types of additives, kinetic strength increased with increasing additive content. In each of the analyzed cases, the obtained values of density of pellets produced from a mixture of straw and bread waste, as well as the kinetic strength, allow for the conclusion that the obtained pellets, in this respect, meet the requirements of ISO 17225-2:2021 and ENplus standards for Class A1 pellets.

Keywords: pellets; solid biofuel; straw; bakery waste; bread; energy properties

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1. Introduction

Biomass, in its many forms, (i.e., wood waste, energy crops, grass, straw, and other types of agricultural and food waste) has, for many years, been used as an energy source. The proper utilization of agro-food waste using green technology is important to reduce the negative environmental impacts of these wastes, which is consistent with the circular economy (CE) [1].

The International Renewable Energy Agency [2] estimates that around three-quarters of the world's renewable energy consumption is bioenergy (energy created from natural sources: plants, animal manure, landfills, biomass waste), of which more than half is the traditional use of biomass (combustion of biomass in such forms as wood, animal waste, and traditional charcoal). A recent report indicates that by 2030, biomass will have been the source of 60% of the world's energy. According to Jha et al. [3], biomass can be grouped into agricultural and forestry biomass, energy crops, oilseed crops, food waste, municipal solid waste, and animal manure. These waste resources can be transformed into biofuel products using thermochemical technologies that consist of torrefaction, pyrolysis, gasification, liquefaction, and transesterification. Due to the increase in demand for wood pellets, there were problems with a sufficient amount of raw material in the form of sawdust. Therefore, raw materials other than wood sawdust began to be sought and used for the production of pellets.

A potential raw material of this kind used for the production of renewable fuels in the form of pellets or briquettes is the straw from cereals, herbal plants, legumes, decorative plants, etc. [4]. Straw is the residual material left on farms after the completion of a plant production cycle. The utilization of straw by the energy industry seems to be an optimal solution as it yields diverse benefits. Straw is one of the most attractive feedstocks for energy production in Poland, after wood. Proszak–Miąsik et al. [5] state that a total of 30-million tons of straw is produced annually, of which there is a surplus of approximately 13.5-million tons of undeveloped straw. For energy purposes, straw from cereals or rapeseed is used the most often. In Poland, a large amount of oat straw is produced, with no alternative use for it. Ren et al. [6] claim that the development of new technologies (liquefaction, gasification, solidified energy production, and biochar production) has allowed for a more common and more economically profitable use of straw for energy purposes. Thanks to these technologies, the conversion of straw for energy purposes has become less energy-intensive and more environmentally friendly by reducing emissions of pollutants into the atmosphere.

Hernández–Neri et al. [7] produce fuel pellets from mixtures of rice husks and bean straws, as well as mixing ratios of the biomasses (rice husks: bean straws). They show that pellets obtained from 90% bean straw and 10% rice husk, with a moisture content of 15%, meet the requirements of the ISO 17225-6 standard [8].

Domański et al. [9], examining the process of co-pelletization of corn straw with the addition of plastics, points out that thanks to the use of additives improving the calorific value of biomass fuels, they can improve the economics of production.

In recent years co-pelletization has been one of the most researched methods for the production of fuel pellets. In their study, Platace et al. [10] produced fuel pellets from mixtures of grass biomass and wood biomass in order to find the proportion of ingredients most suitable for its production. Their research has shown that adding the appropriate amount of wood waste to reed biomass significantly reduces the chlorine content in the received product. In other studies, the authors [11] produced pellets from mixtures of reed, timothy (*Phleum pratense* L.), switchgrass (*Panicum virgatum* L.) with pine, and spruce sawdust. They found that mixing pine sawdust with other types of biomass reduces energy consumption during pelleting and, consequently, reduces the costs of pellet production [11]. Matkowski et al. [12] produced pellets from wheat straw as well as pellets with the addition of cassava starch and calcium carbonate testing the strength and water absorption of the pellets. They observed a strong and positive correlation between the values of specific pellet compression work, the elasticity modulus for pellet compression, and tensile strength. Chojnacki et al. [13] produced pellets from barley straw with waste generated during juice production. They observed that the addition of apple, carrot root, and red beetroot pomace to barley straw resulted in an increased density and hardness of pellets.

In the production of fuel in the form of pellets or briquettes, other waste materials are increasingly often used apart from wood waste, e.g., waste from the fruit and vegetable industry [14–16].

A type of waste additive that can be added to mixtures before pelleting is bakery waste, e.g., bread. According to Demirci et al. [17], bread is a commonly wasted food in most developed countries, particularly in Europe, where it is consumed the most. Globally, it is estimated that around 10% of all the produced bread is wasted. Bread waste can be generated at the stage of production, transport, and distribution. According to Guo et al. [18], the addition of starch binder in the form of bread waste improves the mechanical and physicochemical properties of the pellet.

In Poland, bread waste is used to feed animals, while if signs of microbiological infection are detected in it, it is disposed of by combustion or composting [19] in this raw material.

Wijayarathna et al. [20] examined ther-like properties using microorganisms. Riaukaite et al. [21] confirmed the viability of using bread waste to produce glucose. Many different acids can be also produced from bread waste using appropriate microorganisms [22]. Leung et al. [23] developed a new bio-refining concept for the use of bread waste as a source of nutrients for the fermentative production of succinic acid by *Actinobacillus succinogenes*.

The synthesis of flavoring esters from bread is an example of a method used in the perfumery and food industries in order to improve the aroma of products as desired by consumers and the reduction of the cost of production [24].

The aim of this study was to determine the effect of the addition of bakery waste (5 to 15%) on the course of the process of pelleting of triticale straw and the assessment of the quality of the obtained pellets. The research allowed for the determination of the appropriate content of bakery waste in fuel pellets made from triticale straw—maintaining the adequate physical (mechanical) and energy properties while at the same time enabling a reduction of the costs of electricity used for fuel production.

2. Materials and Methods

2.1. Materials

Bread waste in the form of white ("baltonowski"), wholegrain, and sunflower seed bread was used in the study (Figure 1).

(**a**)

(**b**)

(**c**)

Figure 1. Raw materials used in the study (own photos): (**a**) White bread (during drying and crumbled); (**b**) Wholegrain bread before and after grinding; (**c**) Sunflower seed bread.

The bread was purchased as a feed material, i.e., bakery products returned from stores located in the city of Białystok. Straw from winter triticale, sourced from the 2021 harvest, was also used in the pellet production process (Figure 2).

Figure 2. Triticale straw (own photos): (**a**) Before grinding; (**b**) After grinding.

The process of preparing the raw material began with the initial fragmentation of the bread with the use of a slicer, and the initial drying of the bread with the use of an electric heater. Then, the dried bread was crushed using a "BK" H 111/1 hammer mill to a particle size of approximately 2 mm (using a grinder sieve with a mesh size of 2 mm).

Triticale straw was crushed in the same way. Sieves with a mesh size of 3 mm were used for crushing the triticale straw.

2.2. Determination of Bulk Density

Bulk density of the raw materials was determined pursuant to PN–EN ISO 17828:2016-02 [25] by filling a container (with an effective inner diameter of 167 mm and an effective inner height of 228 mm) with a known volume of material (the top surface was leveled). Bulk density was defined as the ratio of material weight (using an OHAUS AX224M analytical balance (with the measurement accuracy $\pm$ 0.1 mg)) to container volume.

2.3. Determination of Particle Size Distribution

The process of sieve analysis of straw was carried out pursuant to PN–R–64798:2009 [26] using a programmable LPz-2e shaker by Multiserv Morek for sieve analysis and an OHAUS AX224M analytical balance (with the measurement accuracy $\pm$ 0.1 mg). During the analysis, a set of seven sieves with square mesh side dimensions of 6 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm was used. The sieve analysis was performed five times on a 100 g sample of sawdust. The mean value of the obtained determinations was taken as the final result.

2.4. Determination of Moisture Content

The moisture content of the raw materials prior to pelleting was determined pursuant to PN–EN ISO 18134-1:2015-11 [27] with the use of an AXIS AGS moisture analyzer with an accuracy of 0.01%. During the tests, each time the moisture content of five samples was determined. Samples weighing 0.005 kg were taken for the measurement and dried at 105 °C. The average values of the obtained determinations were taken as the final results of moisture determinations.

2.5. Determination of Carbon, Nitrogen, Hydrogen, and Sulfur Content

The contents of carbon, nitrogen, hydrogen, and sulfur were determined pursuant to PN–EN ISO 16948:2015-07 [28], and PN–EN ISO 16994:2016-10 [29] standards using a LECO CHN628 analyzer.

Precision range of the analyzer: C-: 0.01 mg or 0.5% RSD, H-: 0.05 mg or 1.0% RSD, N-: 0.03 mg, or 0.6% RSD. Analyzed sample mass in the analyzer is up to 250 mg (100 nominal mg), and analysis time is 5.5 min.

The contents of carbon and hydrogen in dry biomass were determined by high-temperature combustion with IR (infrared) detection; the content of nitrogen—by the catarometric method pursuant to 16948:2015-07 [28], where a 0.0001 kg sample was weighed in accordance with the requirements for the analysis. The sulfur content was determined by high-temperature combustion with IR detection, i.e., pursuant to PN–EN ISO 16994:2016-10 [29], and a 0.0003 g sample was weighed.

2.6. Determination of Ash Content

Determination of the ash content in the raw materials consisted in incinerating the samples at a temperature of 575 ± 25 °C, and then calculating the ash content pursuant to PN–EN ISO 18122:2016-01 [30], using the following Formula (1):

$$ASH = \frac{m_{tp} - m_t}{m_{ts} - m_t} \cdot 100\% \quad (1)$$

where:

m_t—Mass of the crucible [kg],
m_{ts}—Total weight with raw material [kg],
m_{tp}—Mass of the crucible with ash [kg].

2.7. Determination of Calorific Value and Heat of Combustion

The calorific value and the heat of combustion of the raw materials were determined pursuant to PN–EN ISO 1928:2002 [31] and the methodology described previously in publications [32,33] using the KL–12M calorimeter by PRECYZJA-BIT.

The calorific value Q_s^a of the tested raw materials was determined and used to calculate the heat of combustion Q_i^a by entering the contents of volatile matter, moisture, ash, and sulfur into the calorimeter software. The calculations were performed using Formula (2):

$$Q_i^a = Q_s^a - 24.43\ (w + 8.94\ H^a) \left(\mathrm{kJ \cdot kg^{-1}}\right) \quad (2)$$

where:

w—Moisture content of the sample (%),
H^a—Hydrogen content of the sample (%),
24.43—Coefficient that accounts for the heat of water vaporization at 25 °C in pellets with a 1% water content,
8.94—Coefficient that accounts for the stoichiometry of the hydrogen combustion reaction (quantitative changes).

2.8. Pellet Production

After analyzing the raw materials, the pelleting process began, and mixtures of winter triticale straw with the addition of 10, 15, and 20% of crushed bread, i.e., wholegrain bread, white bread, and sunflower seed bread, were prepared for this purpose.

A Bosch PSB 6-16 RE 600 drilling machine with a special mixer was used to prepare the mixtures of straw and bread with appropriate water content uniformly. The moisture content of the prepared mixtures was 17%, and it was obtained by adding a specific amount of water to the mixtures, knowing the moisture content of the mixture components. The mixing process was conducted in plastic containers, which, after mixing the raw materials in them, were tightly closed and left for 24 h.

In order to determine the moisture content of the mixtures before pelleting, an AXIS model AGS weight dryer was used.

All the mixtures were subjected to the process of pressure pelleting in an SS-4 test stand (Figure 3) equipped with a P-300 pelletizer (driven by Y132M electric motor, 7.5 kW, 1440 obr· min^{-1}) from Protechnika, with flat die roller compactors pursuant to the methodology described previously in publications [34,35]. The stand was equipped with a vibrating conveyor Fritisch Laboret 24, which feeds the mixture into the pelletizer, and a Watt meter (Metrol KWS 1083, max 20 kW), measuring the pelletizer's power demand/energy consumption. The mass flow rate of the mixture through the peletizer's working system was 40 kg/h.

Figure 3. The view of the laboratory SS-4 stand: 1—Working system of granulator with a flat matrix; 2—Electric motor driving the granulator; 3—Feed of raw material; 4—Spill granulate; 5—Vibrating conveyor; 6—Universal meter for measuring the power demand; 7—Rejestrator Spider; 8—PC computer.

During pelleting, a matrix with a hole diameter of 6 mm was used, while the working gap between the rollers and the matrix was 0.4 mm. The obtained pellets were left to cool for 24 h, after which further tests were conducted.

2.9. Pellets Density and Bulk Density of Pellets

In order to determine the pellet density, their edges were leveled using an EINHELL WSG–125E angle grinder (with a motor power of 850 W and a blade diameter of 125 mm); the pellet length was then measured using a caliper with an accuracy of 0.05 mm. Pellets prepared in this way were weighed. The final result of the pellet density was the arithmetic mean determined on the basis of measurements carried out for 10 pellets. The pellet density was calculated using the following Formula (3):

$$\rho_g = \frac{m_g}{V_g}\left[\mathrm{kg}\cdot\mathrm{m}^{-3}\right] \tag{3}$$

where:

ρ_g—Density of the obtained pellets [kg·m^{-3}],
m_g—Mass of the obtained pellets [kg],
V_g—Volume of the obtained pellets [m^3].

The volume of pellets was determined using the following Formula (4):

$$V_g = \pi\cdot r^2\cdot h\left[\mathrm{m}^3\right] \tag{4}$$

where:

r—Radius of pellets [m],
h—Height of pellets [m].

The bulk density of the pellets was determined pursuant to PN–EN ISO 17828:2016-02 [27] by filling a container with a known volume with pellets (the top surface was leveled). The container with pellets was weighed using an OHAUS AX224M analytical balance (with the measurement accuracy $\pm$ 0.1 mg). Bulk density was defined as the ratio of pellet weight to container volume.

2.10. Kinetic Durability of Pellets

The kinetic durability (kinetic strength) of pellets was determined pursuant to PN–EN ISO 17831-1:2016-02 [34] and according to the methodology described previously in publications [32,33].

During the tests, the pellets were passed through a 5 mm sieve to remove fine fractions, and 100 g of the pellets remaining on the sieve were placed in a Holmen NHP tester, which cascades them (for 60 s) in an air stream at 70 mbar, causing the pellets to collide with each other and the perforated metal surfaces of the test chamber.

After the test, they were passed through the same sieve. The pellets remaining on the sieve were weighed (on an OHAUS AX224M analytical balance), and the PDI was calculated according to Formula (5):

$$P_{dx} = \frac{m_2}{m_1} \cdot 100\% \ [\%] \tag{5}$$

where:

P_{dx}—Kinetic durability of pellets [%],
m_1—Mass of the sample before the test [kg],
m_2—Mass of the sample after the test [kg].

2.11. Pellet Emissivity from Combustion

Emissivity during pellet combustion was determined on the laboratory station (Figure 4), including a Moderator Unica VentoEko boiler and Dr. Födisch MCA10 flue gas analyzer.

Figure 4. Low-Emission Combustion Technologies laboratory stand: 1—Moderator Unica VentoEko 25 kW boiler; 2—Controller of the boiler; 3—Fuel tank; 4—Exhaust-sampling place; 5—MCA10 analyzer; 6—Microsoft tablet for archiving obtained measurement results.

The MCA 10 analyzer enables continuous measurements of emissions in exhaust gases (including CO, NO, N_2O, NO_2, NH_3, CH_4, HCl, SO_2, and HF, as well as TOC as a system), and the measurement of CO_2, H_2O, and O_2. The measurement inaccuracy of the analyzer is <2% of the measurement range. It has the ability to automatically correct the zero point.

Pellet combustion was carried out in standard operating mode, with an airflow of 22%, a burner power of 19.7 kW, and a fuel stream of 3 kg·h^{-1}. The obtained results, concerning the contents of the tested compounds (CO_2, CO, NO, SO_2, and HCl) in exhaust gases, were normalized to 10% of oxygen content (O_2), according to the Formula (6):

$$Z_{s2} = \frac{21 - O_2'}{\left(21 - O_2''\right) \cdot Z_{s1}} \left[\%,\ \mathrm{mg \cdot m^{-3}}\right] \quad (6)$$

where:

Z_{s1}—Actual content of the chemical compound in flue gases [%, mg·m^{-3}],
Z_{s2}—Content of the chemical compound in flue gases for a given oxygen content [%, mg·m^{-3}],
O_2'—Set oxygen content in exhaust gases [%],
O_2''—Actual oxygen content in exhaust gases [%].

Based on the obtained results, arithmetic means and standard deviations were calculated for the purpose of interpretation.

2.12. Statistical Analysis

Statistical analysis was conducted in the Statistica 13.3 (StatSoft Inc., Tulsa, OK, USA) [35]. In order to compare the power demand of the pelletizer and the kinetic strength of pellets produced with the addition of white bread waste, and wholegrain bread waste, sunflower seed bread waste in the amount of 5, 10, 15%, the analysis of variance (ANOVA) was applied. This analysis made it possible to determine whether there are statistically significant differences between the selected physical properties of pellets, which would depend on the percentage share of different types of bread. The qualitative factor or independent variable against which the selected physical parameters were compared was their percentage share in the tested pellets.

The research results were presented as mean values with standard deviation (SD).

3. Results and Discussion

3.1. Determination of Bulk Density

Table 1 shows the bulk density and the ash content of raw materials.

Table 1. Results of measurements of bulk density of raw materials and the ash content.

Raw Material	Bulk Density [kg·m^{-3}]	SD	Ash Content [%]	SD
White bread	634.43	13.17	2.55	0.15
Sunflower seed bread	551.25	4.94	2.30	0.02
Wholegrain bread	664.96	11.51	2.97	0.06
Triticale straw	84.35	3.13	4.77	0.03

Baking waste was characterized by similar bulk densities, i.e., 634.43 kg·m^{-3} and 551.25 kg·m^{-3} for white bread and sunflower seed bread, respectively, and 664.96 kg·m^{-3} for wholegrain bread. Winter triticale straw was characterized by decidedly the lowest bulk density among all the tested raw materials, i.e., only 84.35 kg·m^{-3}. Significant differences in the bulk density of the mixture components may cause separation during transport, as well as uneven feeding of a mixture with the appropriate composition to the pelletizer. It is, therefore, important for the mixture to be mixed as it is being transported from the storage tank to the pelletizer.

Bakery waste was characterized by similar ash contents, ranging from 2.30% for sunflower seed bread to 2.97% for wholegrain bread. The average ash content in the white bread used for pelleting was 2.55%. Winter triticale straw was characterized by an ash content of 4.77%. In general, the addition of bread waste to wheat straw reduces the ash content in the pelleted mixture, thus improving the quality of the produced pellets in terms of their fuel properties and the requirements for the ash content in fuel pellets as set by standards.

3.2. Granulometric Distribution of Raw Materials

Table 2 shows the granulometric composition of the raw materials used for pelleting. The results of the tests of the granulometric composition of the raw materials showed that the dominant fraction in the case of bread waste was the fraction with a particle size of 0.5 mm. For each of the raw materials, the smallest fraction of bread particles was the fraction retained on the sieve with a mesh size of 0.063 mm. In each case, it was below 0.50%. The largest percentage by weight, i.e., 40.47%, for winter triticale straw, was characteristic for the particle fraction retained on a 2 mm sieve, while the smallest fraction of only about 0.80% was characteristic for the fraction retained on a 4 mm sieve.

Table 2. Granulometric distribution of raw materials used for pelleting.

	Fraction Share [%]							
Sieve [mm]	White Bread		Sunflower Seed Bread		Wholegrain Bread		Triticale Straw	
	Average	SD	Average	SD	Average	SD	Average	SD
4	0.24	0.03	0.40	0.01	0.69	0.05	0.80	0.05
2	2.40	0.24	6.96	2.22	3.75	0.29	40.47	0.93
1	23.03	0.60	23.90	2.91	25.73	1.24	39.65	0.97
0.5	46.74	1.10	31.92	1.86	45.64	1.37	11.48	0.66
0.25	20.83	1.43	31.62	3.23	17.56	0.34	4.67	0.41
0.125	6.51	0.46	4.85	0.21	6.31	0.28	1.74	0.35
0.063	0.05	0.01	0.04	0.01	0.05	0.01	0.85	0.10
≤0.063	0.02	0.01	0.30	0.02	0.27	0.05	0.34	0.02

Maj and Piekarski [36] draw attention to the need for the optimal preparation of straw chop due to its granulometric composition. According to their study, the highest efficiency of the process of pelleting of wheat straw was obtained for the optimum chaff length of 3–8 mm. It was not possible for a fraction that was too small to compact into the form of pellets, while a fraction that was too long clogged the pelleting channels. Similar conclusions were reached by Niedziółka et al. [37], who indicated that the optimal fraction for the pelleting of wheat and corn straw was 3–5 mm.

On the basis of the tests, it was found that the moisture content of white bread was 13.18%, while the lowest value of this parameter, i.e., 11.09%, was found for wholegrain bread. The moisture content of triticale straw that was not dried before grinding was 12.60%.

The mixtures subjected to pelleting were characterized by an average moisture content ranging from 16.38%, in the case of the mixture with a 5% content of wholegrain bread, to 17.04%, for the mixture with a 15% content of sunflower seed bread.

3.3. Moisture of Tested Materials

Table 3 presents the results of the tests of raw materials subjected to pelleting and of the mixtures before pelleting.

According to Matkowski et al. [12] and Nath et al. [38], who studied the process of straw pelleting with various additives, the optimal range of moisture content for the pelleted mixture was approximately 18–20% due to the formation of durable pellets with the highest bulk density and kinetic strength. Niedziółka et al. [37], who examined the process of the pelleting of wheat, rapeseed, and corn straw, indicate that the optimum range of moisture content for the pelleting of material is 18–22%. Maj and Piekarski [36] indicate that the optimum moisture content for the pelleting of wheat and barley straw should be approximately 14%, but they point out that this parameter depends on the design of the pelletizer. Raila et al. [39], examining the impact of straw moisture on the energy consumption of the pelleting process, point out that water present in the raw material changes the physical properties of the processed straw and has a negative impact on pelleting efficiency when the moisture content of the processed straw is 14%; when the moisture content of straw increases to 23.45%, the efficiency of pelleting drops to 0.75 $t \cdot h^{-1}$. Domański et al. [9], conducting research on corn straw pelleting with plastic waste, point out that the water content in the tested material affects the processing and forming of granulate in the granulator. As part of their experiments, they found that the humidity of raw materials intended for granulation should not exceed 20%. Moreover, the manufacturers of pelletizers recommend that straw should be pelleted with moisture contents of 15% [40], 12–15% [41], or 10–18% [42].

Table 3. Moisture contents of raw materials and mixtures subjected to pelleting.

Raw Material	Content of Bakery Waste [%]	Moisture Content [%]	SD
White bread waste	5	16.549	0.23
	10	16.422	0.333
	15	16.382	0.223
	100	13.18	0.0305
Wholegrain bread waste	5	16.705	0.359
	10	16.534	0.283
	15	16.391	0.179
	100	11.69	0.243
Sunflower seed bread	5	16.833	0.101
	10	16.606	0.437
	15	17.049	0.325
	100	11.09	0.235
Triticale straw (dry)	100%	12.6	0.137
Triticale straw (moistened for palletization)	100%	16.17	0.328

The authors' own experience shows that when pelleting straw with the use of the existing pelletizers, the optimum moisture range of the pelleted material should be approximately 17%. The results of measurements of the moisture content of raw materials showed the need for adding moisture to the mixtures in order to achieve the quoted value of this parameter required for the proper course of the process.

3.4. Ultimate Analysis of Raw Materials

Table 4 presents the results of the elemental analysis of raw materials (bakery waste and triticale straw) subjected to pelleting.

Table 4. Results of the elemental analysis of the raw materials.

Raw Material	C ± SD [%]	H ± SD [%]	N ± SD [%]	S ± SD [%]
White bread	39.52 ± 0.11	8.54 ± 0.04	1.81 ± 0.03	0.19 ± 0.01
Sunflower seed bread	46.19 ± 0.39	9.19 ± 0.04	2.74 ± 0.05	0.29 ± 0.01
Wholegrain bread	40.33 ± 0.08	8.49 ± 0.03	1.44 ± 0.05	0.16 ± 0.01
Triticale straw	42.49 ± 0.08	7.62 ± 0.02	0.49 ± 0.02	0.09 ± 0.01

The results show that the highest carbon content was found in sunflower seed bread (46.19%), which may be due to the content of seeds in the bread and the oil present in the seeds. This is also confirmed by the highest hydrogen content (9.19%) found in sunflower seed bread, in comparison with the other tested waste materials. The high carbon and hydrogen contents have a positive effect on the calorific value of fuels, as evidenced by the highest heating value of sunflower seed bread.

The highest nitrogen content (2.74%) was obtained for sunflower bread with seeds. Slightly lower values of nitrogen content were obtained for white bread (1.81%) and wholegrain bread (1.44%), and the smallest values (0.49%) were obtained for triticale straw. According to Yuan et al. [43], nitrogen in biomass occurs in the form of proteins, DNA, RNA, chlorophyll, alkaloids, and porphyrins, and its presence in thermally processed biomass is undesirable mainly due to the emission of harmful nitrogen oxides NO_x.

For example, the nitrogen content of the wood granulate is 0.12–0.13%. Most of the standards for wood pellets [44] require that the pellets contain less than 0.3% nitrogen. The EN Plus A2 certificate [44] specifies the maximum nitrogen content below 0.5% and the EN Plus B certificate below 1%. Therefore, the pellets from straw meet the criteria of the EN Plus A2 certificate, and the pellets from straw with bread addition meet the criteria of the EN Plus B certificate [44].

The highest sulfur content (0.29%) was observed in sunflower bread with seeds. Slightly lower values of sulfur content were obtained for white bread (0.19%) and wholegrain bread (0.16%), and the smallest values (0.09%) were obtained for triticale straw. According to the DIN–Plus certificate and the ONORM M7135 standard, the sulfur content in wood pellets should not exceed 0.04%. Obernberger [45] claims that exceeding the content of 0.2% by weight sulfur in biomass results in high SOx emissions.

3.5. Heat of Combustion and Calorific Value of the Raw Materials

Results of measurements of the heat of combustion and the calorific value of the raw materials used in the pellet production process are presented in Table 5.

Table 5. Heat of combustion and caloric value of raw material.

Raw Material	Moisture Content [%]	Heat of Combustion [MJ·kg^{-1}]		Caloric Value [MJ·kg^{-1}]	
		At the Analytical Moisture	For Dry Weight	At the Analytical Moisture	For Dry Weight
White bread	13.18	14.51	17.41	15.83	18.72
Sunflower seed bread	11.69	15.06	17.49	16.33	18.75
Wholegrain bread	11.10	14.36	16.85	15.64	18.11
Triticale straw	12.60	14.93	17.72	16.86	19.58

Among the tested breads, the lowest calorific value, i.e., 15.64 MJ·kg^{-1} (at a moisture content of 11.10%), was found for wholegrain bread. In the case of white bread with a moisture content of 13.18%, its calorific value was 15.83 MJ·kg^{-1}. The highest calorific value was found in sunflower seed bread, which was 16.33 MJ·kg^{-1} at a moisture content of 11.69%.

Straw from winter triticale had a calorific value of 16.86 MJ·kg^{-1} (at 12.60% moisture).

Based on the results presented in Table 5, formulas for converting the heat of combustion and the caloric value of triticale straw and breads depending on their moisture content were developed:

- Heat of combustion of tested material:

$$\text{White bread} \qquad Q_{sb} = -0.22w_b + 19.41 \tag{7}$$

$$\text{Sunflower seed bread } Q_{sb} = -0.21w_b + 19.49 \tag{8}$$

$$\text{Wholegrain bread} \qquad Q_{sb} = -0.22 w_b + 18.85 \tag{9}$$

$$\text{Triticale straw} \qquad Q_{ss} = -0.22\ w_s + 19.72 \tag{10}$$

- Caloric value of tested material:

$$\text{White bread} \qquad Q_{ib} = -0.22\ w_b + 20.72 \tag{11}$$

$$\text{Sunflower seed bread}\ Q_{ib} = -0.21\ w_b + 20.75 \tag{12}$$

$$\text{Wholegrain bread} \qquad Q_{ib} = -0.22\ w_b + 20.11 \tag{13}$$

$$\text{Triticale straw} \qquad Q_{ib} = -0.22\ w_s + 21.58 \tag{14}$$

where:
Q_{ss}, Q_{sb}—Heat of combustion of straw and bread (MJ·kg^{-3}),
Q_{is}, Q_{ib}—Caloric value of straw and bread (MJ·kg^{-3}),
w_s, w_b—Moisture content of straw and bread (%).

Table 6 shows the heat of combustion and calorific value at the same humidity of 15%, calculated according to the Formulas (7)–(14).

Table 6. Heat of combustion and caloric value at the same humidity of 15%.

Raw Material	Moisture Content [%]	Heat of Combustion [MJ·kg^{-1}]	Caloric Value [MJ·kg^{-1}]
White bread	15	15.43	14.11
Sunflower seed bread	15	15.65	14.37
Wholegrain bread	15	14.77	13.49
Triticale straw	15	16.34	14.40

By analyzing the values presented in Table 6, it was found that all of the tested breads had slightly lower values of the heat of combustion and calorific value at the same humidity of 15%, in relation to straw. Their addition in the amount of 5 to 15% to the straw will slightly reduce the heat of combustion and calorific value of the produced pellets.

For example, in the case of the addition of wholegrain bread (with the lowest heat of combustion and calorific value), increasing its addition from 0 to 20% causes a decrease in the heat of combustion by 0.31 MJ·kg^{-1} (approximately 1.71%) and a decrease in calorific value by 0.18 MJ·kg^{-1} (approximately 1.11%).

In the case of the addition of sunflower seed bread, increasing its addition from 0 to 20% causes a decrease in the heat of combustion by 0.14 MJ·kg^{-1} (approximately 0.76%) and a decrease in calorific value only by 0.006 MJ·kg^{-1} (approximately 0.04%).

In the case of the addition of white bread, increasing its addition from 0 to 20% causes a decrease in the heat of combustion by 0.18 MJ·kg^{-1} (approximately 1%) and a decrease in calorific value only by 0.06 MJ·kg^{-1} (approximately 0.35%).

The effect of binder addition to the pelleted mixtures on the heat of combustion and calorific value of the obtained pellets was also determined in other works of the authors [15,46,47].

Gendek et al.'s [48] research shows that the caloric value of a mixture of pine sawdust and pine cones ranged from 17.98 MJ·kg^{-1} for pure pine sawdust to 18.32 MJ·kg^{-1} for crushed cones [49]. Similar values were recorded in the present study.

El–Sayed and Khairy [50] found an increase in the heat of combustion of pellets from crushed corn cobs when they added 40% of wheat dust as a binder to this raw material.

They noted an increase of fixed carbon content after a pelleting process of the material from 18% for raw corn cobs and 8.3% for raw wheat dust, respectively, to 29% for corn cobs and 15.8% for wheat dust, which resulted in an increase in the heat of combustion from 16.6 MJ·kg^{-1} to 24.92 MJ·kg^{-1} for corn cobs and from 14.61 MJ·kg^{-1} to 25.35 MJ·kg^{-1} for wheat dust.

Jasinskas et al. [51] stated during the research that the calorific value of three cannabis varieties with a moisture content of 9.98 to 8.87% were 17.37 MJ·kg^{-1} and 16.93 MJ·kg^{-1} dry mass, respectively.

3.6. The Granulation Process and the Characteristics of Pellets

In the case of pelleting of winter triticale straw alone, the average power demand of the pelletizer (Figure 5) was 1.27 kW (which gives a specific energy consumption of 31.75 kW·h·t^{-1} of raw material at a mass flow rate of the mixture through the pelletizer working system of 40 kWh·h^{-1}). For all types of bread, their addition to mixtures with winter triticale straw reduced the power demand of the pelletizer compared to the process of pelleting triticale straw alone. The largest decrease in the power demand of the pelletizer, which was by 13.72%, from 1.25 to 1.04 kW (specific energy consumption from 31.25 to 26 kW·h·t^{-1}), was recorded by increasing the addition of sunflower seed bread from 5 to 15%. The smallest decrease—by 1.81%, from 1.14 to 1.08 kW (specific energy consumption from 28.5 to 27 kW·h·t^{-1}) was observed in the case of an increase in the addition of wholegrain bread from 5 to 15%.

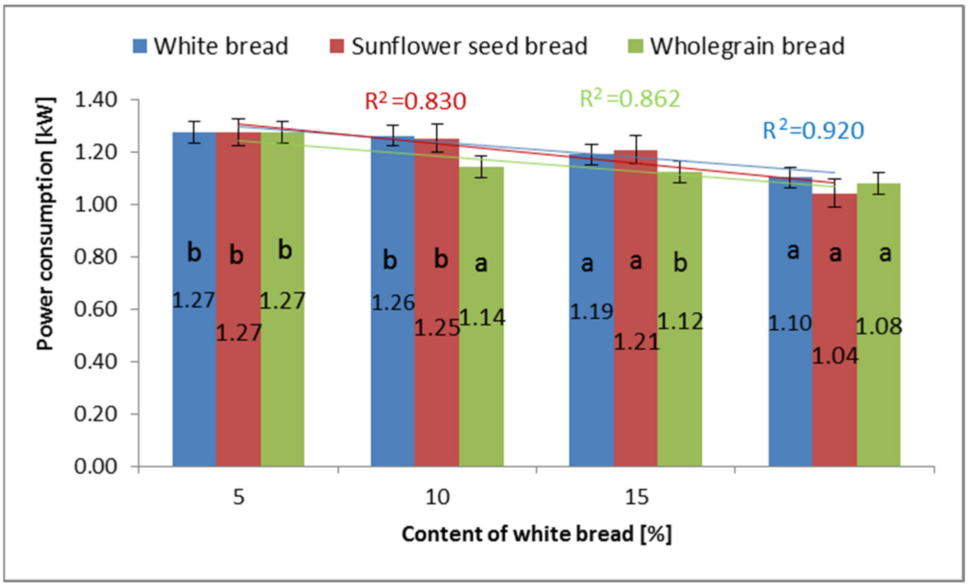

Figure 5. The relationship between the power demand of the pelletizer and the addition of bread. The same letters in the columns next to the mean values mean no statistically significant differences compared with the Tukey test at $\alpha < 0.05$.

The influence of the addition of bread waste on the power demand of pelletizer *Ng* during triticale straw pelleting in the working system of a flat matrix pelletizer is described by the following equations:

$$\textit{white bread waste } Ng = -0.058z_b + 1.350 \quad (15)$$

$$\textit{wholegrain bread waste } Ng = -0.059z_b + 1.300 \quad (16)$$

$$\textit{sunflower seed bread waste } Ng = -0.073z_b + 1.375 \quad (17)$$

where:

z_b—Bread waste content in the mixture (%).

Matkowski et al. [12] pelleted wheat straw with the addition of cassava starch and calcium carbonate. They concluded that unit compaction work, relative to dry matter, was the highest for wheat straw without additions, i.e., 18.1 kJ·kg^{-1}. The addition of cassava starch reduced this value to 14.7 kJ·kg^{-1} (i.e., by 19%); for calcium carbonate addition, the work was reduced to 12.5 kJ·kg^{-1} (by 31%). However, a concentration of these additives had no significant effect on unit compaction work as its values formed a homogeneous group with an average value of 13.0 kJ·kg^{-1}.

Obidziński et al. [52] conducted research on the effect of rye bran addition on the process of sawdust pelleting (spruce and pine mixed in a 50/50 ratio). They found that increasing the content of rye bran from 10 to 20% causes a decrease in the power demand of the pelletizer from 11.06 to 8.89 kW. When compacting sawdust alone, the power demand of the pelletizer was 13.06 kW.

Raila et al. [39], analyzing the energy consumption of the straw granulation process, point out that with a straw moisture of 13.50%, the specific energy consumption was almost 148 kWh·t^{-1}; while at a higher humidity level of 23.45%, energy consumption increased to 171 kWh·t^{-1}.

According to Cui et al. [53], who produced fuel pellets from wood waste biomass and microalgae, with the addition of 50% of microalgae, the minimum energy consumption of 25.2 kJ·kg^{-1} was obtained (in optimal conditions, respectively: temperature 120 °C, pressure 120 MPa, and humidity 10%).

According to Szyszlak–Bargłowicz et al. [14], binder additions from 10, 30, and 50% of copra cake to miscanthus biomass reduced energy consumption during the pelletization significantly decreased energy consumption from 84.45 Wh·kg^{-1} to 39.09 Wh·kg^{-1}.

Tumuluru [54], who pelletized mixtures of pine and switchgrass biomass, recorded a decrease in energy consumption to approximately 90 kWh/ton with an increase in the addition of pine biomass. Tumuluru also recorded that the increase in the mixture humidity resulted in an increase in the value of specific energy consumption.

3.7. Pellets Density and Bulk Density of Pellets

Table 7 presents the results of measurements of pellet density and bulk density of the produced straw pellets with various bread waste-based additions.

Table 7. Average pellet density and bulk density of the produced pellets.

Straw Pellet Type	Mass Fraction of the Additive [%]	Bulk Density [kg·m^{-3}]	Pellets Density [kg·m^{-3}]
Without additives	0	494.66	1194.81
With the addition of white bread	5	515.19	1253.88
	10	486.71	1234.69
	15	434.57	1215.02
With the addition of wholegrain bread	5	534.39	1208.36
	10	472.89	1229.30
	15	458.20	1236.48
With the addition sunflower seed bread	5	468.44	1195.65
	10	407.50	1216.01
	15	384.68	1133.50

The bulk density of pellets made from triticale straw alone was 494.66 kg·m^{-3}. Increasing the addition of bread to winter triticale straw from 5 to 15% caused a decrease in the bulk density of the obtained pellets. When the content of white bread was increased from 5 to 15%, the decrease in bulk density was 80.62 kg·m^{-3}.

A similar situation also occurred in the case of wholegrain bread, when increasing its content resulted in a decrease in density at a level of 76.19 kg·m^{-3} for sunflower seed bread, the decrease was 83.76 kg·m^{-3}. The highest bulk density (approx. 534.39 kg·m^{-3}) was achieved by pellets with a 5% content of wholegrain bread; the lowest bulk density was achieved by pellets with a 15% addition of sunflower seed bread, i.e., approximately 384.68 kg·m^{-3}.

The density of pellets made from triticale straw alone was 1194.81 kg·m^{-3}; 1215.02 kg· m^{-3} at a 15% additive content white bread. Density of pellets produced with the addition of wholegrain bread increased with increasing additive contents from 1208.36 kg·m^{-3} at a 5% additive content to 1236.48 kg·m^{-3} at a 15% additive content, while the density of pellets produced with the use of sunflower seed bread reached 1195.65 kg·m^{-3} at a 5% additive content, 1216.01 kg·m^{-3} at a 10% additive content, and 1133.50 kg·m^{-3} at a 15% additive content.

According to Obidziński and Hejft [55], their research indicates that increasing the addition of rye bran from 10 to 20% causes a slight increase in pellet density from 1190.72 to 1218.6 kg·m^{-3}. The density of pellets made from sawdust alone was 1183.73 kg·m^{-3}. A different trend was observed for the bulk density of pellets, which decreased from 646.5 to 584.73 kg·m^{-3}. The bulk density of sawdust pellets was 722.03 kg·m^{-3}.

Hernández–Neri et al. [7] produced fuel pellets from mixtures of rice husks and bean straws. They stated that pellets produced from 90% bean straw and 10% rice husk with 15% moisture content fulfill PN–EN ISO 17225-6:2021-12 standard [56]. At these conditions, fuel pellets have 610.78 kg·m^{-3} bulk density and 99.51% durability.

3.8. Kinetic Durability of Pellets

Pellets made from pure triticale straw, i.e., without the addition of bread waste, were characterized by the lowest kinetic durability of 95.56% (Figure 6). The addition of bread waste in each of the tested samples led to an increase in the kinetic durability of the pellets. The addition of white bread to triticale straw resulted in the obtaining of pellets with the highest kinetic durability among all the tested mixture variants. At a 5% additive content, it was 97.76%, while at 10%, it was approximately 99.03%; the highest kinetic durability of 99.43% was obtained at a 15% addition of white bread. In the case of the variant of the mixture that contained wholegrain bread, the kinetic durability increased from 96.26% at a 5% additive content to 99.23% at a 15% additive content. Pellets with a 5% content of sunflower seed bread reached a kinetic durability of 97.86% after pelleting; in the case of a 10% waste content (98.23% at a 15% content), it was 98.50%. These pellets (in terms of kinetic durability) respect the requirements of ISO 17225-2:2021 and ENplus standards for Class A1 pellets (kinetic durability above 98%) [57].

The influence of the addition of bread waste on the kinetic durability of P_{dx} pellets obtained during pelleting in the working system of a flat matrix pelletizer is described by the following equations:

$$\textit{white bread waste}\ P_{dx} = 1.288 z_b + 94.732 \quad (18)$$

$$\textit{wholegrain bread waste}\ P_{dx} = 1.281 z_b + 94.057 \quad (19)$$

$$\textit{sunflower seed bread waste}\ P_{dx} = 0.919 z_b + 95.247 \quad (20)$$

where:

z_b—Bread waste content in the mixture (%).

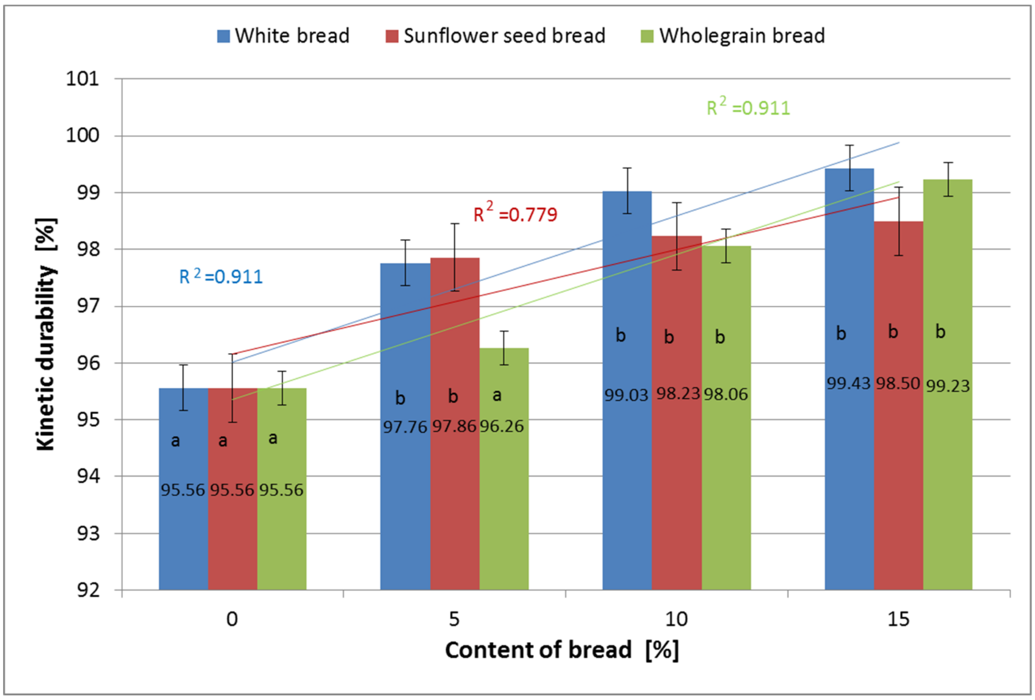

Figure 6. Durability of pellets depending on the addition of bread. The same letters in the columns next to the mean values mean no statistically significant differences compared with the Tukey test at $\alpha < 0.05$.

In each of the analyzed cases, the addition of bakery waste increased the kinetic durability of the pellets. This increase was due to the content of starch, which, as studies conducted by Sołtys [58], Borowski [59], Wróbel [60], and Obidziński and Hejft [55] have shown, improves the pelleting conditions by binding water and through pasting to create additional bonds between pellets.

Similar conclusions were reached by Chojnacki and Zdanowicz [61], who examined the effect of the addition of wheat grain meal, in amounts of 4.2 and 8.1%, to pelleted straw. They found that grit improves the mechanical properties of pellets by increasing their hardness, thus also improving their resistance to abrasion. The addition of 4.2% of wheat middlings increased the hardness of pellets in relation to pure straw pellets by approximately 15%, from 249.6 to 287.6 N. Pellet made from a mixture of straw with the addition of 8.1% wheat middlings was harder by over 60%.

In their study on the effect of rye bran addition on the process of sawdust pelleting (spruce and pine mixed in a ratio of 50/50), Obidziński et al. [52] determined that increasing the addition of rye bran from 10 to 20% results in an increase in the kinetic durability of the pellets from 96.71 to 98.08%. The kinetic durability of pellets made from sawdust alone was 94.25%.

Furthermore, Cui et al. [53], who produced fuel pellets from wood waste biomass and microalgae, found that the addition of microalgae to wood waste in amounts of 15, 30, and 50% can effectively increase the bulk density and mechanical strength of the pellets by 9–36% and 0.7–1.6%. With the addition of 50% of microalgae, a maximum bulk density of 1580.2 kg·m^{-3}, a kinetic strength of 98%, was obtained (in optimal conditions, i.e., temperature of 120 °C, pressure of 120 MPa, and 10% humidity, respectively).

Raila et al. [39], who analyzed the energy consumption of the straw pelleting process, pointed out that for a straw moisture content of 13.5%, the specific energy consumption was almost 148 kWh·t^{-1}; while at a higher humidity level of 23.45%, the energy consumption increased to 171 kWh·t^{-1}.

Stasiak et al. [62] found that pellets obtained from pine sawdust mixed with ground rapeseed straw are characterized by greater durability and impact resistance. Their research showed a decrease in pellet strength with increasing moisture content and an increase in strength with increasing pelleting pressure.

Gaze et al. [63], when comparing the strength properties of pellets made from coniferous wood sawdust, wheat straw, and hemp waste, found that the mechanical strength of wheat straw pellets was only 1% lower than that of wood pellets, while the mechanical strength of all three types of pellets exceeded 97.5%, which makes it possible to classify these biofuels as the highest class of biomass fuels—A1. Gorzelany et al. [64] also point out that even in the case of wood pellets, their strength properties depend on the type of wood used for pellet production. In their research, they compared several different pellets available on the market made from hardwood and softwood waste. The lowest kinetic strength of pellets (95.74%) was obtained for pellets made of hardwood (beech) wood waste, and the highest (98.66%) for pellets made of coniferous material.

As far as the results for kinetic strength obtained in the tests are concerned (Figure 6), it was noticed that, in most cases, straw pellets with the addition of bakery waste can be classified as Class A1 biomass fuels.

The view of exemplary pellets made of triticale straw mixtures with various additives of wholegrain bread waste is shown in Figure 7.

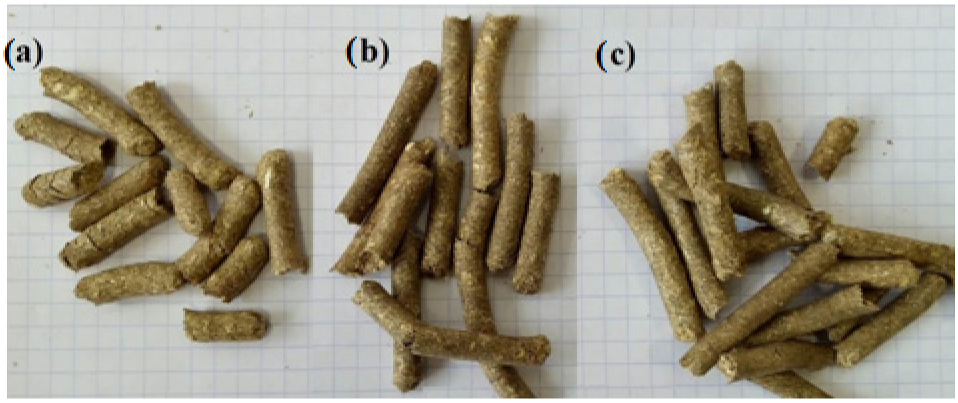

Figure 7. The view of the pellets made of triticale straw mixtures with wholegrain bread waste in the amount: (**a**) 5%, (**b**) 10%, (**c**) 15%.

3.9. Combustion Process of Straw Pellets with the Addition of Bread Waste

Table 8 presents the results of the flue gas composition obtained during the combustion of pellets made from triticale straw with the addition of bread waste in the amounts of 5, 10, and 15%. On the basis of the results, it can be concluded that increasing the content of bakery waste results in a decrease in emissivity as far as CO_2 proportions are concerned, observed for all the pellets produced with the addition of bread waste.

During the combustion processes, special attention is paid to the content of CO in flue gases, as it is an indicator of the presence of hydrocarbons, soot, dioxins, and furans [65]. The maximum CO content in heating boilers with a capacity below 0.5 MW (according to PN–EN ISO 303-5:2012) [66] for class 5 is 500 mg·m^{-3}, with a 10% content of O_2. In the case of CO emission, even the smallest addition of bread waste contributes to its increase. Sunflower seed bread has the greatest potential for increasing CO emissions, while wholegrain bread is the lowest. In the case of a 15% addition of sunflower seed bread, CO emission was 1867.37 mg·m^{-3}. According to the Commission Regulation (EU) of 28 April 2015 [67], the permissible emission of this type of pollutant is 500 mg·m^{-3} of exhaust fumes, so in the case of wholegrain bread, it was exceeded by as much as 373.47%. Hence, pellets produced with the addition of bakery waste did not meet the CO emission standards.

Table 8. Emissions of exhaust gases from the combustion of triticale straw pellets with different additions of bread waste.

Straw Pellet Type	Mass Fraction of the Additive [%]	Flue Composition at 10% O_2					λ [-]	Exhaust Gas Temperature at the Outlet from the Boiler [°C]
		CO_2 [%]	CO [$mg \cdot m^{-3}$]	NO [$mg \cdot m^{-3}$]	SO_2 [$mg \cdot m^{-3}$]	HCl [$mg \cdot m^{-3}$]		
Without additives	0	3.80	166.39	74.94	12.41	36.77	2.70	185.5
With the addition of white bread	5	1.84	1356.46	36.78	10.80	16.55	3.47	177.4
	10	1.72	1254.82	52.71	9.99	15.26	3.53	167.4
	15	1.62	1174.93	57.39	9.19	14.80	3.61	157.2
With the addition of wholegrain bread	5	2.52	964.09	77.31	22.43	18.25	3.03	152
	10	2.52	1338.01	93.34	31.47	18.05	2.88	148.8
	15	2.52	1765.01	101.13	35.75	17.75	2.78	152.8
With the addition of sunflower seed bread	5	2.63	883.00	91.41	13.68	20.88	3.17	145.6
	10	2.17	1310.50	91.14	13.39	21.01	3.23	147.8
	15	2.05	1867.37	113.90	13.11	21.42	3.30	154.2

The tested pellets did not exceed the permissible NO content. In the case of pellets produced with the addition of white bread, the emission of this type of pollutant decreased with each of the tested contents of the additive, compared to pellets made from pure winter triticale straw. All the tested pellets met the standard set by the Commission Regulations (EU) of 28 April 2015 [67] for Class 5 boilers, i.e., 200 $mg \cdot m^{-3}$ of flue gases. The final result for the emissions of nitrogen oxides is affected by the nitrogen content in the fuel and the combustion conditions. According to Rybak [68], the content of NO emissions in flue gases is also largely influenced by the low value of the excess air coefficient and the low combustion temperature.

The addition of bread waste contributed to a reduction of hydrogen chloride emissions for all the produced mixtures in comparison with pure straw pellets. Measurements show that the highest concentrations of HCl occur in flue gases produced during the combustion of pellets with a 15% addition of sunflower seed bread, i.e., 21.42 $mg \cdot m^{-3}$. The lowest value was obtained in the case of a 15% addition of white bread, i.e., 14.80 $mg \cdot m^{-3}$. As far as the combustion of pellets made from straw is concerned, the use of this type of additive may contribute to a reduction of the risk associated with corrosive and toxic effects of chlorine and hydrogen chloride [69].

The lambda coefficient (excess air coefficient) for all the tested pellet variants was lower than 4, which proves the correct contact of the fuel with the oxidizing agent, i.e., air. In the case of the tested pellets, the addition of bread waste contributed to a slight increase in the analyzed coefficient. However, it remained within the accepted range. In the case of pellets with a 15% addition of wholegrain bread, a decrease in the λ coefficient was observed, which eventually reached 2.78.

In the case of sulfur oxide emissions, they are lower for pellets produced with the addition of white bread. In the case of the rest of the tested pellets, SO_2 emission was higher compared to the result obtained for pellets made from pure winter triticale straw. According to Ściążko et al. [70], the amount of emitted SO_2 is affected by the direct return of sulfur in the combusted fuel where with its increase, its emission to the environment also increases. Kraszkiewicz et al. [71] points out that in the case of the analysis of SO_2 emissions during the combustion of biofuels, the adopted combustion system is also important. The combustion of solid biofuels on the grate causes uncontrolled emissions of CO and SO_2 to the atmosphere, which is especially visible in the initial phase of combustion, immediately after placing a portion of fuel on the heating layer and at the end of its combustion.

Analyzing the results of the composition of flue gases for pellets produced from winter triticale straw and with the addition of bread waste, a significant increase in CO emissions can be seen. This is a factor that may affect the viability of using this type of additive to produce pellets. The correct selection of the combustion parameters, in particular thermal and flow conditions, would certainly reduce emissivity compared to that obtained for pellets with the addition of baking waste. It is worth emphasizing that all the tested pellets meet the emission standards for NO and are characterized by a low emissivity of SO_2 and HCl pollutants in exhaust gases.

4. Conclusions

Due to the recently rising costs of traditional biofuels based on wood waste, producers use other materials with high energy potential or use various types of additives to traditional wood raw materials, often acting as a binder. Popular additives are raw materials from waste biomass (agricultural waste, garden waste, or waste from the food industry). Bread waste is a waste from the food industry that can be used as a binder additive in the process of producing biofuels from biomass.

The tests of the pelleting process of triticale straw with the addition of bakery waste (5, 10, and 15% contents of white bread, wholegrain bread, and sunflower seed bread waste) made it possible to conclude that the addition of these types of waste:

1. Has a significant impact on the energy consumption of the pelleting process and on the quality of the obtained pellets, i.e., density, bulk density, and kinetic durability.
2. Resulted in a decrease in the power demand of the pelletizer. The largest decrease in the power demand of the pelletizer (by approximately 18%, from 1.27 to 1.04 kW) was recorded for a 15% addition of sunflower seed bread to the mixture with straw. In all the analyzed pelleted mixtures, the power demand of the pelletizer also decreased with an increase in the amount of the additive.
3. Caused a decrease in the bulk density of the obtained pellets. The highest bulk density of approx. 534.39 $kg \cdot m^{-3}$ was recorded for pellets containing 5% of wholegrain bread, whereas the lowest—for pellets containing 15% of sunflower seed bread, i.e., approximately 384.68 $kg \cdot m^{-3}$. Pellets made from triticale straw without the addition of bread had a bulk density of 494.66 $kg \cdot m^{-3}$.
4. Causes a significant increase in the kinetic durability of the pellets in relation to pellets made from triticale straw alone. The highest kinetic durability was obtained for pellets made from a mixture of triticale straw with a 15% content of white bread, i.e., 99.43%; a slightly lower value was obtained for pellets with a 15% addition of wholegrain bread, i.e., 99.23%.
5. Contributed to a reduction of hydrogen chloride emissions for all the produced mixtures, in comparison with pellets made from pure triticale straw. During the combustion of the produced pellets, the permissible NO content was not exceeded. In the case of CO emissions, even the smallest addition of bread waste contributed to an increase. The tested pellets did not meet the CO emission standards set by the Commission Regulation (EU) of 28 April 2015. SO_2 emissions were higher during the combustion of pellets with the addition of bread waste compared to the emissivity of pellets made from pure triticale straw.

The test results proved that bakery waste has great potential to be used for common agglomeration in mixtures with winter triticale straw. Its use may turn out to be profitable due to its impact on kinetic strength and its reduction of the power demand of the pelletizer. In addition, the use of this type of food industry waste for the production of fuel pellets would enable effective and extremely simple management of this type of residue.

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