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The Effect of Bakery Waste Addition on Pine Sawdust Pelletization and Pellet Quality

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Abstract: This paper presents research findings on the pelleting process of pine sawdust using bakery waste in a pelletizer. The addition of bakery waste (white wheat–rye bread, whole-grain rye bread, and pumpkin bread) to pine sawdust had a beneficial effect on the kinetic strength of the pellets obtained, an increase of up to approximately three percentage points. The density of pellets with the addition of bakery waste also increased, while the bulk density of the pellets decreased. The addition of bakery waste also had a positive effect on the power demand of the pelletizer. It was reduced from 3.08% (at a 10% addition of white wheat–rye bread) to 22.18% (at a 20% addition of pumpkin bread), compared to the process of compacting pure pine sawdust. In addition, all the pellets containing bakery waste had a lower energy yield (EY) determined based on lower heating value and energy inputs. This index was lower by 53 Wh·kg^{-1} for pine sawdust pellets with a 10% addition of pumpkin bread. The greatest reduction, on the other hand, was by 173 Wh·kg^{-1} for pellets, with a 20% addition of white wheat–rye bread. In each case, an increase in the share of bakery additives resulted in a decrease in the energy yield from the pellets obtained. The smallest reduction in EY was found when pumpkin bread was used as an additive (from 53 to 133 Wh·kg^{-1}). Considering all the parameters analyzed characterizing the pellets obtained, it was concluded that the addition of bakery residues to pelletized pine sawdust should not exceed 10%. Further increases in the proportion of bakery waste did not yield relative benefits, due to the deterioration of the energy characteristics of the pellets obtained.

Keywords: biomass; biomass compaction; fuel pellets; bakery waste

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1. Introduction

The increase in energy consumption and carbon dioxide emissions are concerning issues, with energy remaining a determinant factor in sustainable development. Global energy consumption is projected to rise by approximately 30% by 2050, while the consumption of end products will surpass an estimated 310 quadrillion British thermal units (BTU). Considering these trends, the increase in energy consumption will have an impact on the environment, society, and economic activities [1]. With the increasing demand for energy, the depletion of fossil fuels, climate change, and environmental pollution, there is a pressing need to conduct extensive research on new, environmentally friendly alternative fuels and develop their production [2]. The use of renewable energy not only enhances energy security but also helps mitigate climate change and contributes to sustainable economic development [3]. Another key aspect of sustainable development is appropriate waste management. Bioeconomy based on the production and use of renewable biological resources and their conversion into biologically based products, with added value such as food, feed, materials, and bioenergy, is also important [4]. Globalization and environmental protection regulations compel organizations and producers to implement sustainable development principles in every aspect of their operations. While the concept of sustainable development in production has matured, there remains a need for improvement, particularly in the case of perishable food products [5].

Bread is one of the most popular food items. The decline in the interest in bread and the need to maintain overproduction to ensure its freshness are the main reasons for the increasing quantity of unsold baked goods. Products that remain unsold due to approaching expiration dates or baking defects become bakery waste. Depending on the size of the bakery, the amount of bakery waste can range from a few to even several dozen tons per week. Generally, returned bread constitutes approximately 5–10% of a bakery's production, making unsold bread a challenging material to manage [6].

Food losses and waste is a significant challenge that global civilization faces, and it is a topic that often sparks strong emotions and debates. Food waste is not just an economic issue but also an ethical and environmental one [7]. With the growing demand for the sustainable usage of food waste in a circular economy, one trend is the transformation and utilization of dry waste [8]. The utilization of bakery waste depends on various factors. Bakery waste is often used as animal feed because of its high nutritional value and the fact that it is eagerly consumed by animals. They can be included, for example, in the food rations of sheep [9], poultry [10], or pigs [11]. However, products that are outside the bakery and then returned to it as bakery returns can be used for feed purposes if they do not show signs of microbiological infections. Otherwise, such contaminated bread must be thrown out or disposed of in another way.

Research is underway to investigate the potential of using bakery waste to generate electricity [12], as well as produce biofuels such as bioethanol [13,14] and biogas [8]. Bakery waste contains high-quality fermentable sugars, proteins, and other nutrients, making it a promising substrate for producing chemicals, fuels, bioplastics, pharmaceuticals, and other renewable products through microbial fermentation [15,16]. However, these methods still face various technological challenges and require further research.

A study conducted by Rostocki et al. [17] demonstrated that pelleting through pressure agglomeration is an effective method for processing waste materials generated by various industries. Research has also been carried out on the compaction of various food production wastes for their reuse as solid biofuels [18], animal feed [19], or fertilizers [5]. The production of fuel pellets from biomass requires a careful consideration of certain factors, such as the durability of the pellets and production costs, including energy consumption [20,21]. On the other hand, consumers demand high- and consistent-quality pellets that are available at the lowest possible price. The quality of pellets is affected by the type of raw material, particle size, moisture content, compaction pressure, temperature, and residence time in the thickening chamber [22–25]. Researchers are exploring various methods of using different types of biomass raw materials [26–28] and investigating the factors that affect the efficiency and quality of the production process [29–31]. Additionally, new thermal processing technologies might make biomass pellet production more profitable [32–34]. Research efforts should also focus on identifying suitable raw materials for use as additives in pellet production, as not all biomass materials are appropriate for this purpose [35–37].

For the reasons outlined above, a concept has emerged consisting of utilizing bakery waste as an additive in the process of the pressure agglomeration of pine sawdust. Pine sawdust was chosen as the most popular raw material used for the production of wood pellets, while bakery waste was selected due to the need for its management, especially bakery waste infected with mold.

The resulting pellets, a solid biofuel, can be used for energy purposes through direct combustion. Hence, the objective of this study was to analyze the course of the pelletization process of pine sawdust with the addition of bakery waste in the working system of a pelletizer. The aim was to determine the most favorable process parameters, assess the suitability of bakery waste as a potential binder in the pelletization process of pine sawdust, and evaluate its potential as an additive to potentially increase the calorific value of the resultant pellets. It has been noted that the use of bakery waste as an additive during the production of pellets has not been explored yet. The research results obtained are a response to the market's need to support pellet producers and the management of bakery waste, especially those infected with mold. Additionally, they complement databases of waste raw materials that can be used in the production of high-quality, durable, compact biofuels more sustainably.

2. Materials and Methods

2.1. Materials

For the research, pine sawdust was used, which was a byproduct of the timber industry obtained after the production of boards. Additionally, bakery waste from returns to bakeries was utilized. These materials were shredded using a grinder designed for crushing moist corn grains for silage production (PROFI 480, Gruber Maschinen GmbH, Gaspoltshofen, Austria). The device enables the shredding of entire loaves of bread without the need for preliminary division into smaller portions, significantly speeding up the entire process. Subsequently, the shredded bread was dried using an electric heater and re-shredded using a hammer mill. Pine sawdust are small shavings ($\leq$5 mm), i.e., waste obtained primarily from plants processing round (raw) wood, where the technological process of friction produces a finished product (lumber), generating significant amounts of sawdust. The bakery waste included the following: (1) white wheat–rye bread produced using rye sourdough, wheat flour (approximately 60%), rye flour (approximately 25%), water, yeast, and salt; (2) wholegrain bread made from natural sourdough, type 3000 wholegrain rye flour ground once, water, and salt; (3) pumpkin bread made from natural sourdough with rye flour, wheat–rye flour with added pumpkin seeds, water, and salt. The research process included a number of successive stages; a detailed diagram of the research carried out is presented in Figure 1.

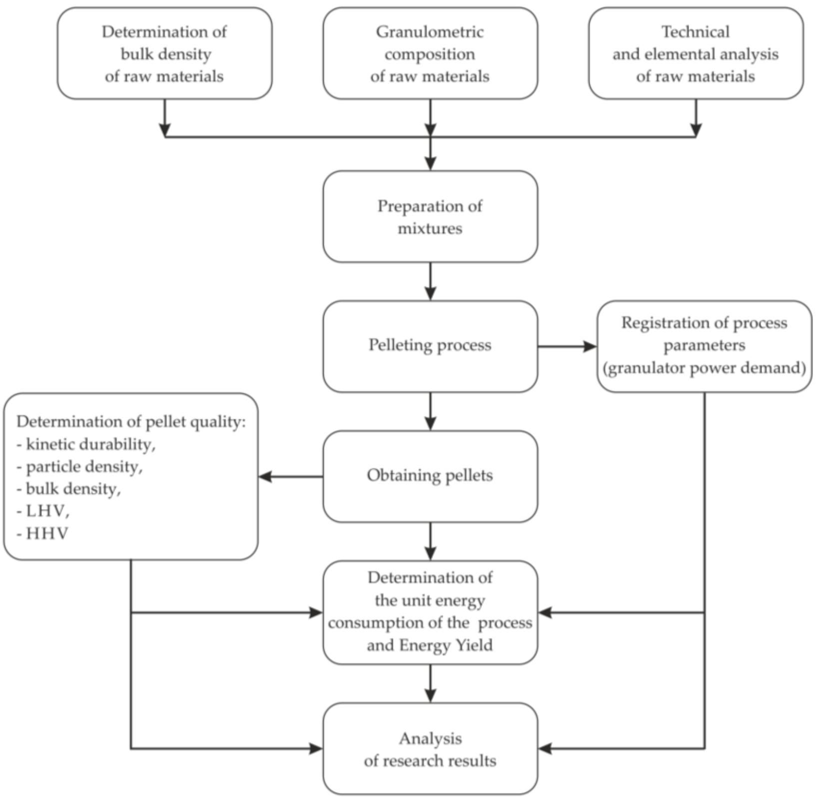

Figure 1. Scheme of the research conducted.

2.2. Preparation of Raw Materials

The raw materials used in the test were prepared in accordance with the EN ISO 14780:2017 standard [38]. The bakery waste was crushed using an analytical grinder (A11, IKA-Werke GmbH and Co. KG, Staufen, Germany) and then dried to minimize the risk of mold growth and to enable safe storage.

2.3. Bulk Density and Granulometric Composition of Raw Materials

The vibrating conveyor (Laborette 24, FRITSCH, Weimar, Germany) was used to determine the bulk density of raw materials for pellet production. The raw material's granulometric composition was determined using a shaker (LPzE-2e, Multiserw Morek, Brzeźnica, Poland) according to the EN 932-1 standard [39]. The sieves in the machine were installed so that their diameter decreased down the machine, with the following order of installation: 4 mm; 3.15 mm; 2 mm; 1 mm; 0.5 mm; 0.25 mm; and 0.125 mm. An analytical balance (ADVENTURER® ANALYTICAL 220G OHAUS, Nänikon, Switzerland) with a reading accuracy of 1 mg was also used.

2.4. Mixture Preparation

The mixtures were prepared on a bench consisting of a weighing balance (SBS-PF-150, STEINBERG SYSTEMS, Berlin Germany). This allows for the weighing of materials from 0.05 to 150 kg with an accuracy of 1 g. To thoroughly mix sawdust with bread, a drill (PSB 6-16, BOSCH, Stuttgart, Germany) with an agitator was used. A measured dose of water was added to increase the moisture content of the mixture to around 17%. Pine sawdust and pre-prepared bakery waste were mixed in various mass proportions (Table 1).

Table 1. The composition of mixtures.

Type of Added Bakery Waste	Mass Fraction of Bakery Waste [%]	Mass Fraction of Pine Sawdust [%]
-	-	100
White wheat–rye bread	10	90
	15	85
	20	80
Wholegrain bread	10	90
	15	85
	20	80
Pumpkin bread	10	90
	15	85
	20	80

The prepared mixtures of pine sawdust and shredded bakery waste were moistened to 17% before the compaction process and conditioned in sealed containers for 24 h.

2.5. Pressure Agglomeration Process

The pelleting process was carried out using an SS-4 test stand (Poland). The stand was equipped with a pelletizer (P-300, Protechnika, Łuków, Poland) that utilizes a 'flat matrix-compacting rollers' working system, as explained in [40]. The pressure agglomeration tests were conducted with a raw material mass flow rate of 40 kg·h^{-1} through the pelletizer's working system. The pelletizer's matrix consisted of 114 holes, each with a diameter of 6 mm. The working gap of the pelletizer was set to 0.4 mm. A vibratory metering device was responsible for the proper dosing of the raw material into the pelletizer's working system. The SS-4 station also included a meter to measure the pelletizer's power demand as well as a recorder (Spider 8, HBK, Darmstadt, Germany). All the data from the sensors were recorded in a continuous manner and saved in the form of binary files. The results of the power demand of the pelletizer were recorded each time a thermal balance in the working system was achieved (a temperature of 85 °C). The pellets obtained were stabilized for 24 h; then, further tests began.

2.6. Pellet Density and Bulk Density

The bulk density of the pellets obtained was determined pursuant to the ISO 17828 standard [41]. They were placed in a cylinder with a volume of 5 l. Their bulk density was determined as the ratio of the mass of pellets to the volume of the cylinder.

The density of the pellets was determined pursuant to the ISO 18847 standard [42], using the hydrostatic method. A density determination kit for solids and liquids, i.e., KIT-85 (Radwag, Radom, Poland), was used, along with the Radwag X3.Y analytical balance with a measurement accuracy of ±0.0001 g. The standard liquid mix of water and a wetting agent (Triton X-100) was used at a concentration of 1.5 g·L^{-1}. The average values calculated from five repetitions were taken as the results.

2.7. Kinetic Durability of Pellets

The pellets' kinetic durability (kinetic strength) was tested 24 h after the pressure agglomeration process using the methodology presented in [43] and the PN-R-64834:1998 standard [44]. The Lignotester (NHP100, Holmen, Stockholm, Sweden) and a laboratory balance (ONYX OX-8100, FAWAG S.A, Lublin, Poland) were used for this purpose. The laboratory balance had a measurement accuracy of 0.1 g. A 100 g pellet sample was placed in the tester's chamber, then subjected to an air stream generated by a blower and impacted on the walls of a perforated metal mesh chamber. The duration of the test for a pellet sample was 60 s. The ratio of the pellet mass after the test to the pellet mass before the test was calculated to determine the pellets' kinetic durability.

3. Results and Discussion

3.1. Properties of Raw Materials and Mixtures

The granulometric composition of the raw materials used for compaction (Table 2) indicates that, for both whole-grain bread and pumpkin bread, the dominant fraction was retained on the 0.5 mm sieve. The results of the study on white wheat–rye bread show that the fraction determined to represent the highest percentage, amounting to 45.28%, was the one retained on the 0.25 mm sieve. In the case of pine sawdust, the predominant fraction, reaching 42.42%, were particles retained on the 1 mm sieve. The >4 mm fraction was only observed in the case of pine sawdust, and its proportion was small, accounting for less than 2.5%. Therefore, taking into account the diameter of the matrix holes, i.e., 6 mm, the recommendations were followed in that the particle sizes of the densified raw material should be approximately 0.5 times the diameter of the matrix hole.

Table 2. The granulometric distribution of raw materials used for pellet production.

	Share of Fraction Retained on the Sieve [%]							
Raw Material	**>4 mm**	**3.15 mm**	**2 mm**	**1 mm**	**0.5 mm**	**0.25 mm**	**0.125 mm**	**<0.063 mm**
Pine sawdust	2.48	2.78	13.86	42.42	21.02	11.36	5.40	0.41
White wheat–rye bread	-	-	0.43	5.28	27.30	45.28	16.48	4.80
Wholegrain bread	-	-	1.32	20.44	46.48	29.40	1.96	0.18
Pumpkin bread	-	-	0.94	12.54	45.80	31.86	8.28	0.20

Among the raw materials investigated, pine sawdust had the lowest bulk density (116.62 kg·m^{-3}), while finely shredded bakery waste had a bulk density that was approximately five times higher (Table 3). A lower heating value (LHV) and the percentage of ash and sulfur contents are the most important criteria for the energy assessment of fuels and biofuels. A technical and elemental analysis of the raw materials used for research showed that bakery waste differed significantly from pine sawdust. Pine sawdust had the highest HHV and LHV (19,229 kJ·kg^{-1} and 17,593 kJ·kg^{-1}, respectively), with the highest moisture content among the tested raw materials, which was approximately 10.65%.

White wheat–rye bread had the lowest LHV at 14,190 kJ·kg^{-1}, with a moisture content of slightly above 7%. The moisture content of the other raw materials was low, i.e., at a similar level (around 6–7%). Attention should be paid to ash content, which was lower in pine sawdust (0.45%) compared to the ash content of the bakery waste (between 2.67% and 3.36%). Upon analyzing the elemental composition of the raw materials used in the study, it was discovered that the sulfur content was more than three times higher, while the nitrogen content was approximately six times higher in the bakery waste as compared to the pine sawdust. This may be important concerning the potential use of pellets obtained from these raw materials for energy purposes. The increased sulfur and nitrogen content in the fuel are linked to the release of oxides of these elements into the atmosphere during their combustion [45,46].

Table 3. Characteristics of raw materials used for pellet production.

Parameter	Unit	Pine Sawdust	White Wheat–Rye Bread	Wholegrain Bread	Pumpkin Bread
Bulk density	kg·m^{-3}	116.6 ± 1.3 ^{a}	577.0 ± 5.2 ^{b}	554.4 ± 3.5 ^{c}	526.7 ± 2.5 ^{d}
Moisture	%	10.65 ± 0.03 ^{a}	7.36 ± 0.01 ^{b}	6.37 ± 0.04 ^{c}	6.98 ± 0.02 ^{c}
Ash	%	0.45 ± 0.01 ^{a}	2.67 ± 0.03 ^{b}	3.06 ± 0.03 ^{c}	3.36 ± 0.10 ^{d}
VM	%	74.02 ± 0.05 ^{a}	68.74 ± 0.26 ^{b}	71.33 ± 0.38 ^{c}	70.40 ± 0.27 ^{d}
FC	%	14.88 ± 0.08 ^{a}	21.23 ± 0.26 ^{b}	19.24 ± 0.42 ^{c}	19.26 ± 0.39 ^{c}
C	%	47.40 ± 0.11 ^{a}	39.52 ± 0.11 ^{b}	40.33 ± 0.08 ^{c}	39.31 ± 0.06 ^{d}
H	%	7.196 ± 0.784 ^{a}	8.537 ± 0.037 ^{b}	8.488 ± 0.030 ^{bc}	8.413 ± 0.050 ^{c}
N	%	0.290 ± 0.027 ^{a}	1.813 ± 0.029 ^{b}	1.537 ± 0.045 ^{c}	1.580 ± 0.037 ^{c}
S	%	0.049 ± 0.006 ^{a}	0.192 ± 0.006 ^{b}	0.159 ± 0.007 ^{c}	0.192 ± 0.009 ^{b}
HHV	kJ·kg^{-1}	19,229 ± 38 ^{a}	15,646 ± 73 ^{b}	16,425 ± 39 ^{c}	16,037 ± 60 ^{d}
LHV	kJ·kg^{-1}	17,593 ± 38 ^{a}	14,190 ± 79 ^{b}	14,401 ± 39 ^{c}	14,751 ± 59 ^{d}

Mean values denoted with the same letter (upper index) in the same row are not significantly different for $p < 0.05$ according to Tukey's HSD test.

Comparing the heating value (LHV) for different biomass types, it was found that bakery waste had a comparable heating value to rye straw [47,48], rapeseed straw [46,49], and spruce sawdust [50]. This makes it possible for bakery waste to be used as additives in pellet production. However, when used as additives to pine sawdust, it may lead to a reduction in the heat of combustion (HHV) and heating value (LHV) of the pellets produced. Moreover, in comparison to pine sawdust, bakery waste contained significantly higher amounts of sulfur, nitrogen, and ash, which are undesirable and harmful components in biofuels. The presence of elemental sulfur in fuels can contribute not only to atmospheric emissions of sulfur oxides but also to the corrosion of power boilers through the deposition of sulfate deposits in the ducts [51]. In a study performed by Gaze et al. [52], a correlation was found between the nitrogen content in biomass and the emission of nitrogen oxides generated during its combustion. Additionally, bakery waste was found to have higher hydrogen and fixed carbon (FC) contents, and lower elemental carbon and volatile matter (VM) contents, compared to pine sawdust.

3.2. Properties of Pellets

The bulk density of pellets produced from pure pine sawdust was one of the highest at 406.5 kg·m^{-3} (Figure 2). The addition of 10% bakery waste in the form of wholegrain bread and pumpkin bread resulted in a decrease in the bulk density of the pellets by several percentage points (approximately 11–16%). Only a 10% addition of white wheat–rye bread resulted in a slight increase in bulk density, amounting to 410.6 kg·m^{-3}. However, increasing the content of waste bread additives to pine sawdust from 10 to 15% and to 20% resulted in a further decrease in the bulk density of the pellets obtained for each of the additives used, except for the 15% addition of whole-grain bread. A higher bulk density of biofuels is advantageous due to the increased efficiency of their transport and the smaller spaces needed for storage. Hence, bulk density influences biofuel transport efficiency, handling, and storage capacity.

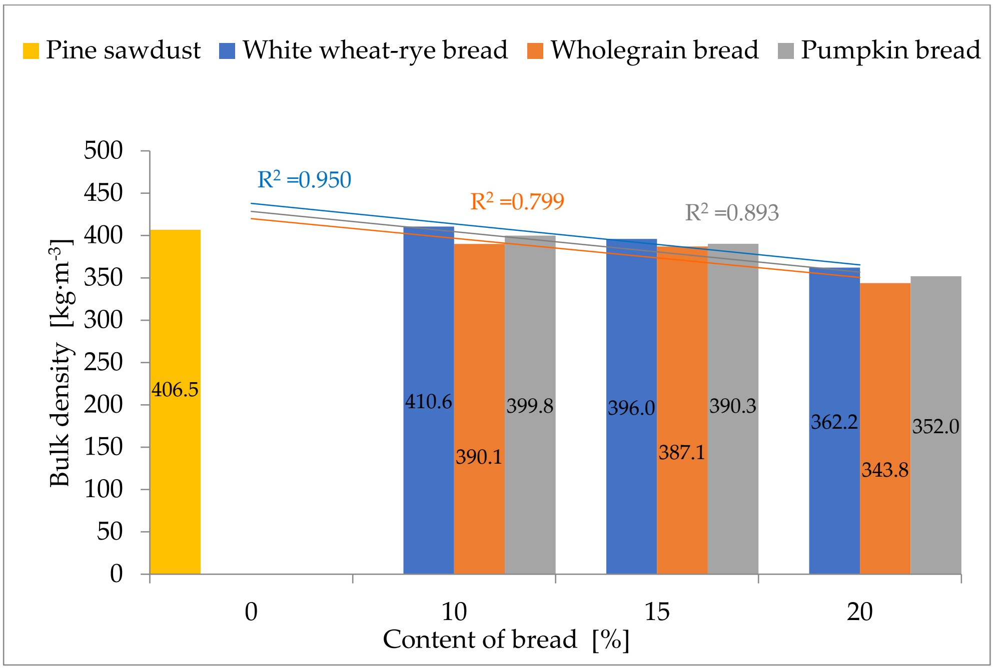

Figure 2. Bulk density of pellets produced with the addition of bakery waste.

The bulk density of pellets is influenced by the density of individual pellets. The density of pellets made from pine sawdust was the lowest at 1140 kg·m^{-3}. Among pellets with additives, the lowest density was obtained for a 10% addition of waste bread (Figure 3). Increasing the proportion of waste bread added to sawdust from 10 to 15% and 20% increased the density of the pellets obtained in each case. A high density of pellets is not a parameter that determines their quality, but it is nevertheless important for the efficiency of transport and the combustion process. The optimal density for high-quality pellets should be above 1200 kg·m^{-3} [53]. None of the investigated pellets had such a density, although it deviated only slightly, ranging from a minimum of 1140 kg·m^{-3} for pellets produced from pine sawdust to 1145 kg·m^{-3} for pellets with a 10% addition of wholegrain bread, up to a maximum of 1187 kg·m^{-3} for pellets with a 20% addition of white wheat–rye bread.

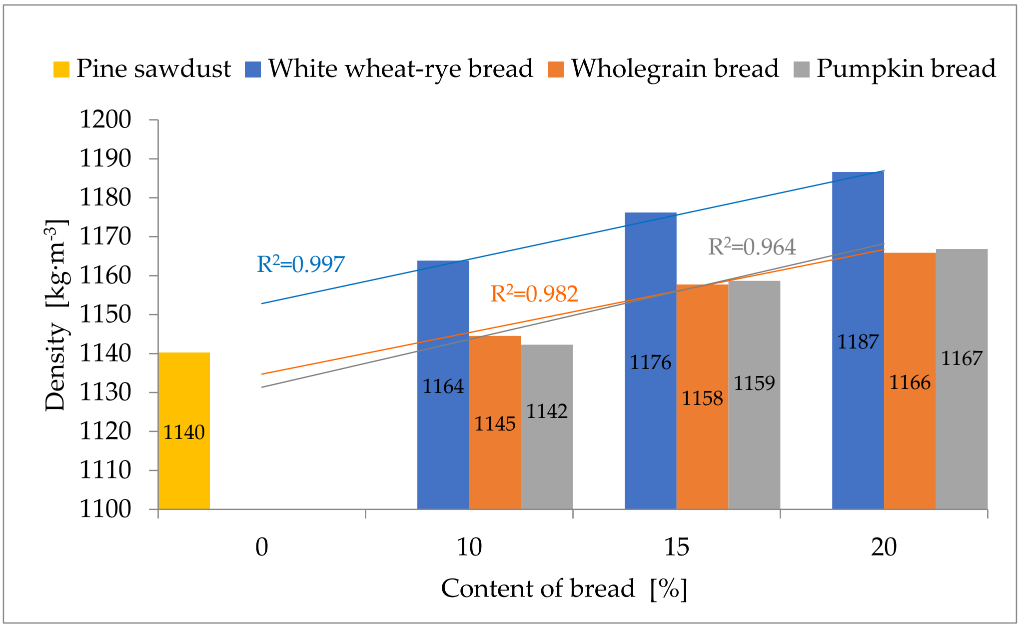

Figure 3. Density of pellets with the addition of bakery waste.

Pine sawdust pellets had the lowest kinetic durability, i.e., 96.4%. This value was slightly below the required threshold, and, in accordance with the standard for pellets used for domestic and industrial purposes (EN 14961-1 [54]), these pellets did not meet the requirements, as the kinetic durability of pellets should be ≥97.5%. However, the addition of bakery waste had a positive impact on the kinetic durability of pellets, leading to increased values of this parameter in all cases (Figure 4).

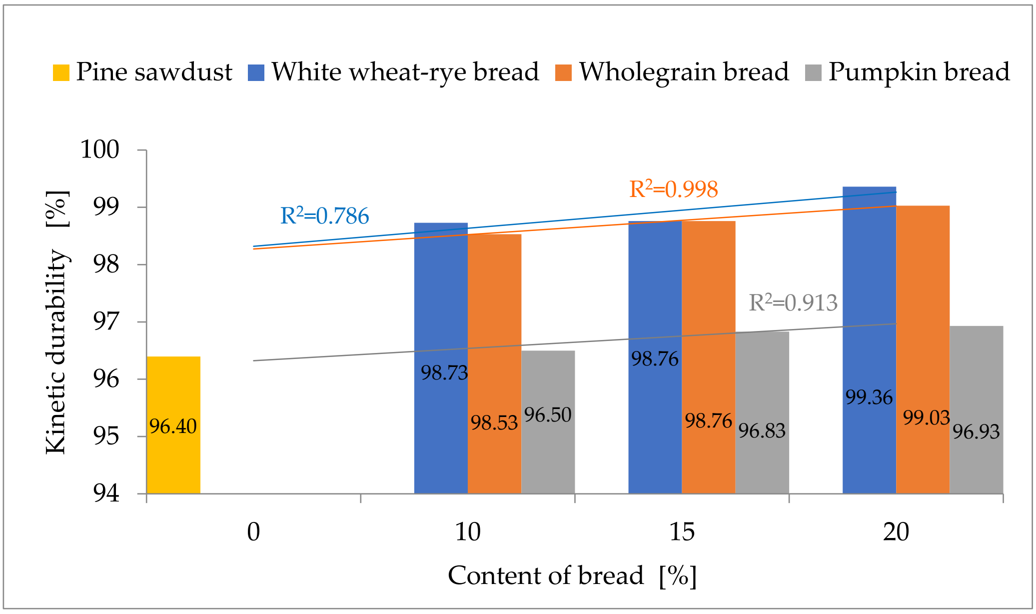

Figure 4. Kinetic durability of pellets with the addition of bakery waste.

The least durable pellets were those produced with the addition of pumpkin seed bread. The least durable pellets, with a kinetic strength of approximately 96.5%, were pellets with a 10% addition of pumpkin bread (which was 1 percentage point below the strength of 97.5% required in the standard). However, the kinetic durability values for pellets with 15% and 20% additions of pumpkin bread were 96.83% and 96.93%, respectively. Therefore, an increase in the amount of pumpkin bread addition led to an increase in the kinetic durability of pellets, although this increase was relatively small.

On the other hand, all pellets produced with the addition of white wheat–rye bread and wholegrain bread exhibited high kinetic durability, exceeding 98%. An increased addition of white wheat–rye bread resulted in an increase in the kinetic durability of pellets (from 98.73% to 99.36%), the values exceeding the minimum specified in the standard (EN 14961). The addition of wholegrain bread also influenced the kinetic durability of pellets, which was high and ranged from 98.53% to 99.03%. It should be noted that kinetic durability is a very important parameter characterizing the quality of pellets. A high value of this parameter reduces issues during fuel feeding, decreases dust emissions during combustion, and affects transportation and storage.

The results available in the literature show a strong influence of individual biocomponents in pelletized mixtures on the densification process and the properties of pellets, depending on the additive used. In a study by Guo et al. [55], the influence of mixing waste biomass and using starch-based binders on the mechanical properties of agropellets was investigated, among other factors. The physical properties of agropellets, such as pellets density, durability, compressive strength, and water absorption, have significantly improved.

According to [56], too high of a fat content in plant raw materials has a negative effect on the strength properties of the product. Ståhl and Berghel [57] confirmed that the energy input during the pelletization of pine sawdust decreases with increasing rapeseed cake content. At the same time, the durability of pellets decreased. Moreover, the bulk density of pellets decreased as the amount of rapeseed cake additive increased. On the other hand, a study by Cui et al. [58] showed that blending microalgae can effectively increase the bulk density and mechanical durability of the product while reducing energy consumption.

3.3. Energy Indicators

Table 4 shows the pelletizer's power demand and energy yield of the pellets produced, as recorded during the tests. The moisture content of all the agglomerated mixtures measured just before the start of the palletization process was approximately 17%. According to studies [59], the correct moisture content of bulk materials to be pelletized should fall in the range of 15–18%.

Table 4. Characteristics of energy consumption in the pressure agglomeration process of pine sawdust and its mixtures with bakery waste.

Parameter	Unit	Pine Sawdust	White Wheat–Rye Bread			Wholegrain Bread			Pumpkin Bread		
Content addition	%	100	10	15	10	10	15	10	10	15	10
Power demand	W	2110	2045	1872	1773	1829	1798	1700	1805	1738	1642
Energy consumption unit ECU	$Wh \cdot kg^{-1}$	52.75	51.12	46.80	44.32	45.72	44.95	42.51	45.12	43.45	41.05
Decrease in ECU compared to pine sawdust	%	-	↓ 3.08	↓ 11.28	↓ 15.97	↓ 13.32	↓ 14.79	↓ 19.43	↓ 14.45	↓ 17.63	↓ 22.18
Decrease in ECU compared to the 10% mixture	%	-	-	↓ 8.46	↓ 13.30	-	↓ 1.69	↓ 7.05	-	↓ 3.71	↓ 9.03
LHV	$kJ \cdot kg^{-1}$	17,593	17,308	17,034	16,938	17,239	17,167	16,988	17,375	17,098	17,073
Energy Yield	$Wh \cdot kg^{-1}$	4834	4757	4685	4661	4743	4724	4676	4781	4706	4701
Decrease in EY compared to pine sawdust	$Wh \cdot kg^{-1}$	-	↓ 77	↓ 149	↓ 173	↓ 91	↓ 110	↓ 158	↓ 53	↓ 128	↓ 133

For all types of bakery waste, its addition reduced the power demand of the pelletizer compared to the compaction process of pure pine sawdust. The reduction ranged from approximately 3% at a 10% addition of white wheat–rye bread, to approximately 22% at a 20% addition of pumpkin bread. At the same time, as the addition of bakery waste increased, the power demand decreased, indicating greater frictional resistance when compacting either pine sawdust alone or mixtures with a lower proportion of bakery waste. The most significant reduction in the power demand (22.18%) was observed during the palletization process of pine sawdust with a 20% addition of pumpkin seed bread. Pumpkin seeds contain oily substances that theoretically should facilitate the palletization process.

The heating value (LHV) of the pellets obtained decreased with an increase in the proportion of bakery waste addition in all cases, reflecting the LHV of these additives. The heating value (LHV) of pine sawdust pellets was 17,593 $kJ \cdot kg^{-1}$, while for pellets with a 10% addition of bakery waste, it ranged between 17,239 $kJ \cdot kg^{-1}$ and 17,375 $kJ \cdot kg^{-1}$. Pellets with a 15% addition of bread had a heating value (LHV) ranging from 17,034 $kJ \cdot kg^{-1}$ to 17,167 $kJ \cdot kg^{-1}$, with the lowest values found for a 20% addition of bread, ranging from 16,938 $kJ \cdot kg^{-1}$ and 17,073 $kJ \cdot kg^{-1}$. Compared to pine sawdust pellets, the maximum difference was observed in the case of pellets containing 20% of white wheat–rye bread, amounting to 655 $kJ \cdot kg^{-1}$. During the compaction process, the highest power demand and energy consumption values were identified for pure pine sawdust. The unit energy consumption (ECU) in this case was 52.75 $Wh \cdot kg^{-1}$. The addition of bakery waste to the pelletized mixture led to a reduction in energy consumption. For instance, adding 10% of wholegrain bread and pumpkin bread resulted in a decrease in this parameter by approximately 7 $Wh \cdot kg^{-1}$.

In order to assess the energy benefits of the pellets, their energy yield was evaluated. The energy yield (EY) from the pellets produced was determined based on their lower heating value (LHV) and the energy inputs associated with their production, using Formula (1).

$$EY = LHV - ECU \quad (1)$$

where

EY—energy yield of pellets [Wh·kg^{-1}],

LHV—lower heating value [Wh·kg^{-1}],

ECU—energy consumption unit [Wh·kg^{-1}].

The lower energy yield (EY) observed for most pellets with added bakery waste was due to the lower heating value (LHV) of the bread, despite the lower energy inputs during the pelletization process for individual mixtures. This indicator was lower by 53 Wh·kg^{-1} for pine sawdust pellets with a 10% addition of pumpkin bread. The greatest reduction, on the other hand, was by 173 Wh·kg^{-1} for pellets with a 20% addition of white wheat–rye bread.

The data presented in Figure 5 show the correlation between the kinetic durability of pellets and their density (Figure 5a) and bulk density (Figure 5b) in relation to energy yield. This analysis helped us to understand the quality parameters of the pellets obtained concerning energy yield. Analyzing the test results presented in Figure 5a, it was found that the addition of bakery waste has a positive impact on the density and kinetic strength of pellets, but, at the same time, it reduces the energy yield. The pellets with 20% white wheat–rye bread had the highest density and kinetic strength but the lowest EY of 4661 Wh·kg^{-1}. Unfortunately, the addition of bakery waste to pine sawdust resulted in a decrease in the bulk density of the pellets (except for 10% white wheat–rye bread) while maintaining high kinetic durability (Figure 5b). The lowest values of bulk density and energy yield were observed for 20% of all the tested additives. From Figure 5a,b, it is evident that using up to 10% of the tested additives is the best way to maintain high-quality pellets and a high energy yield.

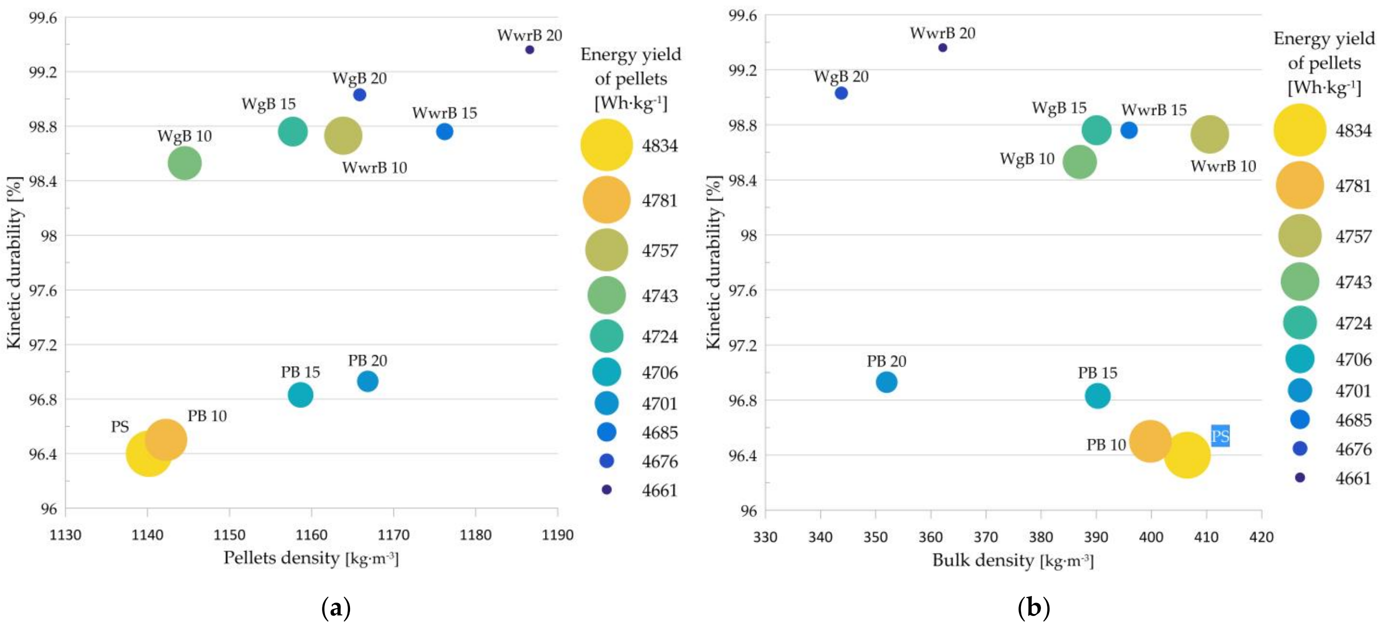

Figure 5. Energy yield (EY) of pellets vs. kinetic durability: (**a**) pellet density and (**b**) bulk density. WwrB—White wheat–rye bread, WgB—Wholegrain bread, PB—Pumpkin bread, PS—Pine sawdust; the numbers next to the symbols represent the percentage of the additive.

The increase in the proportion of bakery waste additives led to a reduction in the energy yield from the pellets obtained. The smallest decrease in the EY indicator was observed when pumpkin bread was used as an additive (from 53 to 133 Wh·kg^{-1}). In a study by Szyszlak-Bargłowicz et al. [60], the authors demonstrated that pressure agglomeration of miscanthus biomass with a 10–30% addition of coconut slurry waste resulted in a reduction in the energy input of the process and an improvement in the properties of the pellets obtained. At the same time, pellets made from miscanthus biomass only had the lowest energy yield at 4758 Wh·kg^{-1}, which is lower than the energy yield obtained from pine sawdust pellets in this study (4887 Wh·kg^{-1}).

The literature provides highly varied values for the power demand of the pelletizer, depending on the type of compacted biomass. For instance, the energy consumption for pelletizing pine sawdust was 180 Wh·kg^{-1}, while for fruit mixtures, it ranged from 90 to 330 Wh·kg^{-1} [31], representing a relatively high energy input. Pelletizing corn cob waste required energy inputs in the range of 80–400 Wh·kg^{-1} [61]. Zawiślak et al. [62] determined the energy consumption for pelletizing chamomile waste and birch sawdust at 108 Wh·kg^{-1} and 100 Wh·kg^{-1}, respectively. In another study by Cui et al. [58], pelletizing hardwood and softwood sawdust resulted in an energy consumption of approximately 13 Wh·kg^{-1} and 10 Wh·kg^{-1}, respectively.

Bakery waste containing high amounts of complex carbohydrates in the form of starch (60–70%) appears to be a more favorable additive in pellet production than agro-food by-products containing fats. Hejft and Obidziński [63] considered mill waste to be a good binder additive for the production of compacted solid biofuels. Their addition, in combination with straw grinding, resulted in the gelatinization of the starch contained in the mill waste, reducing the energy intensity of the unit load between the matrix and the thickening rollers.

3.4. Economical Evaluation

The test results obtained confirmed the positive effect of the addition of bakery waste on the quality properties of the pellets obtained. The use of bakery waste additives is also economically justified. Wood pellet producers do not boast that they use additives to wood raw material in their production process. However, most of them use such additives because the standard permits their use in small amounts (less than 2%). These are most often by-products from cereal processing (e.g., cereal bran, waste products from milling plants, or lower-quality flour) containing starch and protein residues, which have a positive effect on the pelleting process. Despite the affordable price of these raw materials, which are accepted by producers, they constitute a significant cost for them. The economic analysis carried out showed that the use of bakery waste as an addition to sawdust in the production of pellets would be almost twice as cheap compared to the use of cereal bran, the average price (in Poland) of which is currently approximately 200–220 EUR/ton, while in the case of the wholesale purchase of bakery waste from large producers, their price ranges from 110 to 120 EUR/ton.

In general, the use of various types of food waste for energy purposes could become a way to manage and utilize them. Under favorable conditions, a potential exists for replacing approximately 11% of global coal consumption by burning biofuels derived from waste [64]. Pressure- and non-pressure-pelleting processes present untapped potential in the management of by-products and bio-waste. Additionally, various researchers have shown that pelleting can provide effective solutions to various challenges in today's world, aligning with the goals of a sustainable economy. It is also worth noting that pelleting processes use readily available raw materials and additives, such as mineral fillers or water, making the entire operation relatively easy, waste-free, and profitable [17].

4. Conclusions

The economy of the future will not be able to afford convenience and wastage. It is already being described as one that, following the example of ecosystems, will have to be based on a multilevel use of waste [65]. Enhancing the efficiency of primary resource utilization, minimizing waste generation in favor of recycling, and promoting a resource-efficient economy through industrial symbiosis are pivotal objectives of a circular economy. The return of waste to the economy as high-quality secondary source of raw materials can directly affect the reduction in demand for and conservation of primary raw materials [66]. Agriculture and forestry are core sectors in the context of environmental action—ones that produce renewable resources and account for a significant share of the economy. They are one of the major key elements of the circular economy and bioeconomy model.

The use of bakery returns as a biocomponent of wood pellets for energy purposes can be a waste-free, low-cost way to effectively manage this type of waste. However, due to their unfavorable energy parameters—in particular, the low heating value and the high sulfur and ash content—they may negatively impact the properties of the resulting pellets, especially when added in larger quantities. Therefore, burning such pellets would require the use of appropriate combustion and flue gas cleaning system designs to ensure complete and total combustion while minimizing the emissions of sulfur oxides and particulate matter.

The addition of bakery waste to pine sawdust had a positive effect on the kinetic durability of the resulting pellets. All the pellets produced with the addition of bakery waste exhibited a high kinetic strength index exceeding 96%. The bulk density of pellets produced with the addition of bakery waste also increased, while the density of pellets decreased. The addition of bakery waste also had a positive effect on the power demand of the pelletizer. A reduced power demand was observed, ranging from 3.08% (at a 10% addition of white wheat–rye bread) to 22.18% (at a 20% addition of pumpkin seed bread), compared to the compaction process of pure pine sawdust. Therefore, it is possible to reduce the energy consumption of the pellet production process by managing and using bakery waste as an additive. Considering all the parameters analyzed characterizing the pellets obtained, it was found that the addition of bakery waste to pelletized pine sawdust should not exceed 10%. Further increases in the proportion of bakery waste did not bring relative benefits, due to the deterioration of the energy characteristics of the pellets obtained. The most significant benefits were observed when incorporating up to a 10% addition of bakery waste. After testing various additives, it was found that adding white wheat–rye bread was the most beneficial due to changes made in the density, kinetic strength, and bulk density of pellets. When adding pumpkin bread to pelleted pine sawdust, it was recorded that there was a significant reduction in the demand for pelletizer power.

Considering the positive impact of the addition of bakery waste on the quality properties of the pellets obtained, their widespread use as an addition to wood raw material in the production process is justified. The use of such an additive is allowed by the ISO 17225-2 standard [67], according to which, it is possible to use additives to wood raw materials in small amounts (less than 2%) in the production of pellets for commercial and household applications and in certain amounts (less than 3%) in the case of pellets for industrial use. Therefore, the use of bakery waste additives can be legally sanctioned by obtaining certification of such an additive, granted by specialized bodies certifying wood pellet additives.

Another positive aspect of using bakery waste as additives is the possibility of managing large amounts of bakery waste, especially when they are infected with mold and when other possibilities of their management are not possible.

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