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Effect of the Addition of Elderberry Waste to Sawdust on the Process of Pelletization and the Quality of Fuel Pellets

Sławomir Obidziński ¹, Paweł Cwalina ^{1,*}, Małgorzata Kowczyk-Sadowy ¹, Aneta Sienkiewicz ¹,
Małgorzata Krasowska ¹, Joanna Szyszlak-Bargłowicz ², Grzegorz Zajac ² and Rafał Kryński ¹

¹ Department of Agri-Food Engineering and Environmental Management, Białystok University of Technology, Wiejska 45E, 15-351 Białystok, Poland; s.obidzinski@pb.edu.pl (S.O.); m.kowczyk@pb.edu.pl (M.K.-S.); a.sienkiewicz@pb.edu.pl (A.S.); m.krasowska@pb.edu.pl (M.K.); r.krynski@pb.edu.pl (R.K.)

² Department of Power Engineering and Transportation, Faculty of Production Engineering, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland; joanna.szyszlak@up.lublin.pl (J.S.-B.); grzegorz.zajac@up.lublin.pl (G.Z.)

* Correspondence: p.cwalina@pb.edu.pl

Abstract: This paper presents the results of a study on the process of the pelletization of pine sawdust with the addition of herbaceous waste from elderberry, in the working system of a pellet press with a flat matrix, in the context of producing fuel pellets. Based on the research, the impact of the addition of herbal waste in the form of elderberry waste on the granulation process of pine sawdust and the assessment of the quality of the obtained pellets were determined. The addition of herbaceous waste from elderberry to pine sawdust had a beneficial effect on the kinetic durability of the obtained fuel pellets, with an increase of up to approximately 1.3% (from 98.03 to 99.31%). Based on the obtained results, it can be concluded that the mechanical strength of all the tested pellets is higher than 97.5%, which is consistent with the ISO 17225-1:2021-11 standard. The bulk density of pellets with the addition of herbaceous waste from elderberry increased (from 649.34 to 658.50 kg·m⁻³) as did their density (from 1231.38 to 1263.90 kg·m⁻³). The addition of herbaceous waste from elderberry in amounts ranging from 10% to 20% did not have a significant effect on the power requirements of the pelletizer, which decreased compared to the pelletization process of pure pine sawdust. The percentage of this decrease compared to the pelleting process with pure pine sawdust was approximately 10%. The addition of herbaceous waste from elderberry to pine sawdust slightly reduces the energy value (i.e., the heat of combustion and the calorific value) of the obtained pellets. The addition of 30% elderberry waste resulted in a decrease in the heat of combustion from 20.27 to 19.96 MJ·kg_{d.m.}⁻¹, while the calorific value of the pellets decreased from 19.98 to 18.69 MJ·kg_{d.m.}⁻¹ compared to pine sawdust pellets. Hence, adding herbaceous waste from elderberry seems to be a good way of managing large amounts of waste of this kind generated in herbal processing plants. This method of waste management opens new perspectives towards more sustainable and economically effective energy production.



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1. Introduction

The depleting resources of fossil fuels and the desire to reduce the negative impact of humans on the natural environment, including reducing carbon footprints, forces humanity to search for new sources of energy. Renewable energy sources such as wind, solar, or geothermal power are gaining popularity in the European Union (EU), largely due to the various subsidies offered to their users. However, energy from the aforementioned sources is still only an “add-on”. According to data provided by the European Environment Agency (EEA), production from renewable energy sources accounted for 22.5% of the total EU energy production. According to the October 2023 update of Directive 2009/28/EC, 42.5% of energy in the EU must come from renewable energy sources by 2030 [1]. However, EU

Member States are to strive to achieve a share of their energy from renewable sources of up to 45% according to the REPowerEU plan [2].

Currently, the fastest developing concept is the possibility of using biomass as a renewable energy source. Biomass in the form of wood waste, energy plants, grass, and straw has been used for energy purposes for many years. According to information provided by the International Renewable Energy Agency, the demand for primary energy on Earth slowed down to 1.1% in 2022 compared to 5.5% in 2021. The increase in energy production from renewable energy sources to 12.6% resulted in a decline in the share of fossil fuels in energy production of up to 78.9% [3].

The basic raw material for the production of pellets are tree parts resulting from their processing, i.e., sawdust, chips, and shavings. During the process of pelletization, waste parts (i.e., bark, branches, or stumps) resulting from cutting down trees are also processed. This is confirmed by García et al. [4], according to whom, the main raw material for pellet production is wood; however, due to the growing demand for wood pellets, the supply of sawmill residues has increased.

An alternative to wood biomass pellets may be pellets with the addition of waste from the agri-food industry. The growing population requires increasingly more food production, which results in greater amounts of food waste being produced. According to Papaioannou et al. [5], 1.3–1.6 billion tons of food waste and agri-food waste are generated in the world. According to Güleç et al. [6], by selecting appropriate thermochemical methods such as gasification, pyrolysis, transesterification, or liquefaction, it is possible to transform the available waste resources into biofuels. Converting waste into energy has many advantages, i.e., it supports the development of a circular economy, solves problems with waste storage, and enables the partial replacement of fossil fuels [7]. Therefore, efforts have been initiated to find alternative sources of raw materials that could replace conventional wood sawdust to meet the needs of pellet production.

The most popular method of introducing alternative raw materials to the fuel market is co-pelletization. García et al. [8] presented the possibilities of producing high-quality pellets by adding rejected derived fuel (RDF) to pine sawdust. The study showed a positive effect of the addition of RDF on the pelletization process through a reduction in energy consumption with increasing contents of RDF in the mixture. Although the addition of rejected derived fuel improved the bulk density of the pellets, it had a negative impact on the kinetic strength and the calorific value of the finished product. In other studies, the authors produced agro-pellets from corn straw with the addition of food waste rich in starch [9]. They found that this improved the mechanical properties of the pellets. Stulpinaite et al. [10] produced pellets from oak sawdust with the addition of hemp residues. They noticed that the addition of hemp waste slightly reduced the calorific value of the produced pellets, whereas increasing the hemp content in the pellets increased their kinetic strength.

An important aspect of the production of pellets with the addition of waste is the analysis of the physical and chemical properties of the resulting biofuel. Using excessive amounts of additives in the form of waste may result in an increase in gas and particulate emissions [11]. Research shows that the quality and quantity of the emitted exhaust gases are significantly influenced by the condition of the heating installation and its setting [12]. The physical properties of the burned pellets, i.e., the length of the pellet, its kinetic strength, bulk density, and moisture, also have a huge impact on the emissions of exhaust gases [13,14]. It is, therefore, very important to use high-quality raw materials for pellet production. With the development of the biofuel market, the requirements for pellet quality are increasing. For this purpose, the ISO 17225-1:2021-11 standard was introduced, which specifies the requirements for the physical, chemical, and energy properties of industrial and commercial pellets [15]. With the aim of refining waste materials, many studies have been carried out to determine the impact of the addition of waste materials on the quality of pellets. Kamga et al. [16] examined the possibility of using corn spathes and coconut

shells, noting an increase in the calorific value and a decrease in the ash content of the produced pellets.

Waste that can be used through co-pelletization includes herbal waste, e.g., elderberry. According to Jóźwiak [17], most herbal waste is generated in herb processing companies. It is generated during the processing of herbs, packaging, the production of food, cosmetics, and medicinal preparations, but also during the processing of herbal plants, e.g., their final sorting before the drying process, refining, segregation, and packaging of dry herbs.

The most popular method of managing herbal waste is processing it into feed additives or using it directly as feed. According to the research conducted by Mo et al. [18], the addition of extracts of Chinese medicinal herbs in pellets intended for fish feeding resulted in greater growth and improved immunity of the fish. Moreover, according to Zhuang et al. [19], replacing beef cattle feed ingredients with a 30% addition of fermented herbal tea residues resulted in an improvement in the intestinal microflora of the studied group of animals, with the resulting improvement in the overall health of cattle and their response to heat stress. According to Kalak and Dudczak-Hańbuda [20] elderberry pomace contains dietary fiber, which provides sorption properties towards metal ions. Based on the conducted research, they concluded that elderberry waste may be a potentially effective and inexpensive biosorbent that can be proposed for the industrial removal of metal ions from wastewater.

The aim of this study was to determine the effect of the addition of herbal waste in the form of elderberry waste (added in amounts ranging from 10% to 30%) on the process of pelletization of pine sawdust, and to assess the quality of the obtained pellets. The research made it possible to determine the appropriate content of elderberry waste in fuel pellets made from pine sawdust, while maintaining the adequate physical (mechanical) and energy properties. This method of waste management opens new perspectives towards more sustainable and economically effective energy production, by using the available raw materials in a way that not only reduces the amount of waste but also has a positive effect on the entire energy process.

2. Materials and Methods

2.1. Materials

Pine sawdust and elderberry waste were used in the study. The sawdust was obtained from a private sawmill located in the Hajnówka district, the Podlaskie Voivodeship, Poland. The elderberry waste (Figure 1) was obtained from a production plant processing herbs, i.e., RUNO Sp. z o. o., located in Hajnówka. The material is straw created mainly during the production of black tea with an admixture of elderberry.



Figure 1. Raw materials used in the study (own photos): (a) crushed elderberry waste, and (b) pine sawdust.

2.2. Determination of Moisture Content

The moisture content of the raw materials was determined pursuant to PN-EN ISO 18134-1:2015-11 [21], with the use of an AXIS AGS moisture analyzer. During the tests,

the moisture content for five repetitions at a temperature of 105 °C was determined. The average values of the obtained determinations were taken as the final results of the moisture determinations.

2.3. Determination of Ash Content

Determination of the ash content in the raw materials consisted of incinerating the samples at a temperature of 815 ± 15 °C, and then calculating the ash content pursuant to PN-EN ISO 18122:2023-05 [22], using Equation (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} —mass of the raw material [kg];

m_{tp} —mass of the crucible with ash [kg].

2.4. Determination of Bulk Density

The bulk density of the raw materials and pellets was determined pursuant to PN-EN ISO 17828:2016-02 [23], by filling a container with a known volume of material (with an effective internal diameter of 167 mm and an effective internal height of 228 mm). Bulk density was defined as the ratio of the weight of the material volume (measured using an OHAUS AX224M analytical balance (Nänikon, Switzerland), with a measurement accuracy of ± 0.1 mg) to the container volume.

2.5. Determination of Particle Size Distribution

Determination of the granulometric distribution was performed pursuant to PN-R-64798:2009 [24], using an LPz-2e laboratory shaker (Multiserv Morek, Marcyporęba, Poland), consisting of a vibrating base and a set of sieves with square sides of 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm.

2.6. Elemental Composition Analysis

The contents of carbon, nitrogen, hydrogen, and sulfur were determined pursuant to PN-EN ISO 16948:2015-07 [25] and PN-EN ISO 16994:2016-10 [26] standards using a LECO CHN628 analyzer (St. Joseph, MI, USA).

2.7. Determination of Calorific Value and Heat of Combustion

The calorific value and the heat of combustion were determined pursuant to PN-EN ISO 1928:2002 [27] and the methodology described previously in publications [28,29].

The calorific value and the heat of combustion were determined using Equation (2), taking into account the pre-determined contents of moisture, ash, hydrogen, and sulfur where

$$Q_i^a = Q_s^a - 24.43(w + 8.94H^a) [\text{kJ} \cdot \text{kg}^{-1}] \quad (2)$$

Q_i^a —moisture calorific value [$\text{kJ} \cdot \text{kg}^{-1}$];

Q_s^a —combustion heat [$\text{kJ} \cdot \text{kg}^{-1}$];

w —moisture content of the sample [%];

H^a —hydrogen content—of the sample [%];

24.43—coefficient accounting for the heat of water vaporization at 25 °C in pellets with a 1% water content;

8.94—coefficient accounting for the stoichiometry of the hydrogen combustion reaction (quantitative changes).

2.8. Pressure Agglomeration Process

After determining the physical and chemical properties of the tested materials, mixtures of pine sawdust and post-production elderberry waste were prepared. The mixtures contained 10, 20, and 30% additions of elderberry waste. After moistening to the assumed humidity of 13%, they were placed in special containers which, after mixing, were tightly sealed for 24 h to prevent the evaporation of water.

The mixtures were subjected to the process of pelletization at the SS-5 station (Figure 2), the basic element of which is a TechnoMaszBud pelletizer (Słupno, Poland), model Prime-200, equipped with a 12 kW engine with a rotational speed of 1440 rpm. The working system consists of a flat stationary matrix and two rotating rollers.

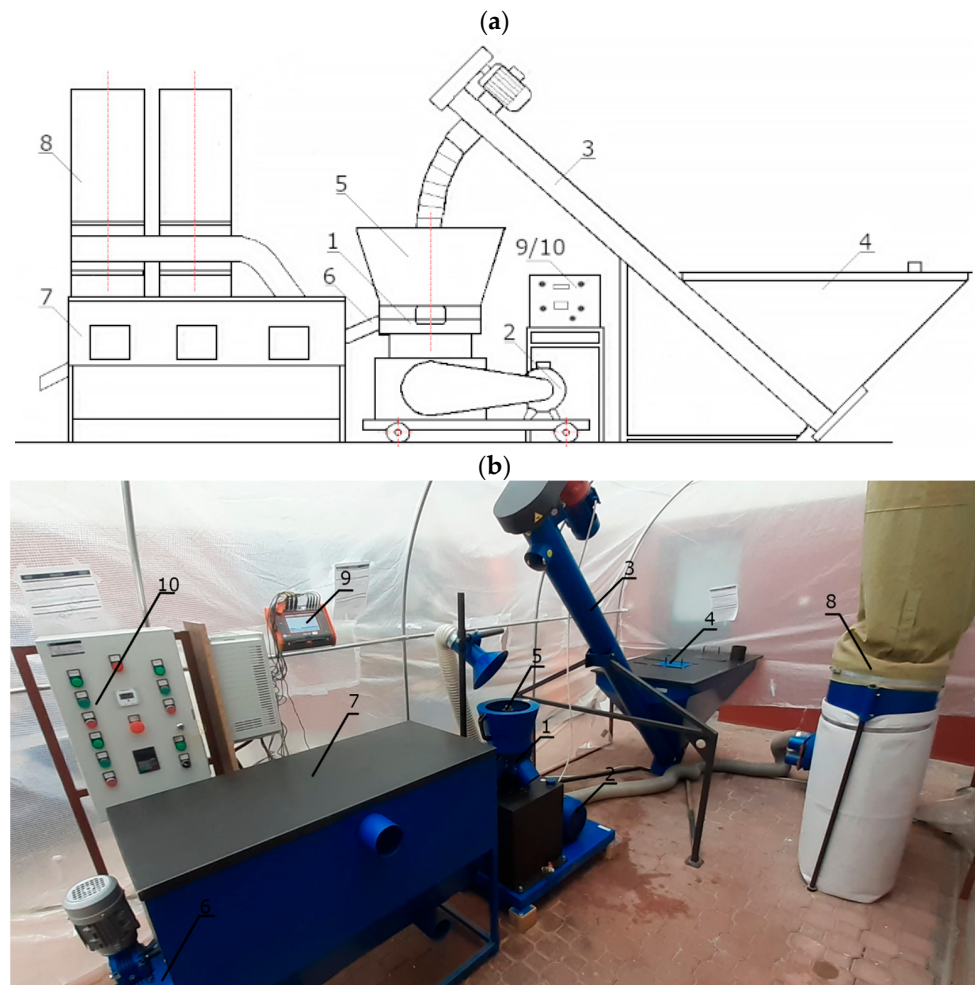


Figure 2. Station SS-5 (own photo): (a) diagram of the station: 1—working system of the pelletizer with a fixed flat matrix, 2—electric motor driving the pelletizer (12 kW, 1440 rpm), 3—screw feeder (PS-200), 4—raw material hopper, 5—raw material hopper, 6—pellet discharge, 7—pellet cooler (KC-100), 8—closed extraction system (SO-2), 9—power consumption recorder (Sonel PQM707), 10—cabinet control, and (b) view of the station.

The SS-5 station is equipped with an autonomous power consumption meter (9) enabling the comprehensive measurement, analysis, and recording of parameters in power grids (DC and 50/60 Hz). All measurements were carried out in class S pursuant to the PN-EN 61000-4-30:2011 standard [30], guaranteeing high accuracy. The obtained results were then read using the Sonel Analysis 4.6.1. The constant values during the research were

- $w_m = 13\%$ —mixture humidity [%];
- $d_o = 6 \text{ mm}$ —diameter of holes in the matrix [mm];

- $Q_m = 50 \text{ kg} \cdot \text{h}^{-1}$ —mass flow rate of the mixture [$\text{kg} \cdot \text{h}^{-1}$];
- $n_r = 124 \text{ rpm}$ —rotational speed of the compaction roller system [rpm];
- $h_r = 0.2 \text{ mm}$ —gap between the rollers and the matrix [mm].

2.9. Physical and Bulk Density of Pellets

To determine the physical density of pellets, 10 representative pellets were selected, and then an EINHHELL WSG-125E angle grinder (Landau, Germany) was used to smooth their edges. The pellets prepared in this way were measured with a calliper with an accuracy of 0.05 mm and then weighed on an analytical scale with an accuracy of $\pm 0.001 \text{ g}$. The density was calculated using Equation (3):

$$\rho_g = \frac{m_g}{V_g} [\text{kg} \cdot \text{m}^{-3}] \quad (3)$$

where

ρ_g —physical density of pellets [$\text{kg} \cdot \text{m}^{-3}$];

m_g —mass of pellets [kg];

V_g —volume of tested pellets [m^3].

The volume of pellets was calculated using Equation (4):

$$V_g = \pi \cdot r^2 \cdot h [\text{m}^3] \quad (4)$$

where

r —radius of pellets [m];

h —height of pellets [m].

The bulk density of the pellets was determined pursuant to the PN-EN ISO 17828:2016-02 standard [23]. A container of known volume was filled with pellets and then weighed on an analytical balance (with a measurement accuracy of $\pm 0.1 \text{ mg}$). Bulk density was calculated as the ratio of the mass of pellets to the capacity of the container.

2.10. Kinetic Durability of Pellets

The kinetic durability of the produced pellets was determined pursuant to the PN-EN ISO 17831-1:2016-02 standard [31] and according to the methodology described in previous publications [32], using the Holmen NHP100 tester (Norfolk, UK). To perform the determination, the pellets were pre-sieved on a 5 mm sieve to remove the crushed pellet fraction. A 100 g sample was then placed in the test chamber, which cascades the pellets in an air stream causing them to collide with each other as well as with the perforated hard surfaces in the test chamber. After the test, the sample was again sieved and the remaining pellets were weighed. The kinetic durability was calculated using Equation (5):

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

where

P_{dx} —kinetic strength of pellets [%];

m_1 —ample weight before test [kg];

m_2 —sample weight after test [kg].

2.11. Energy Indicators of Pellets Production

To determine the energy benefits of the pellets, the energy yield was assessed, taking into account the energy inputs incurred for pellet production using Equation (6):

$$EY = LHV - ECU \text{ [Wh} \cdot \text{kg}^{-1}] \quad (6)$$

where

EY —energy yield of pellets [$\text{Wh} \cdot \text{kg}^{-1}$];

LHV —lower heating value [$\text{Wh} \cdot \text{kg}^{-1}$];

ECU —energy consumption unit [$\text{Wh} \cdot \text{kg}^{-1}$].

Equation (7) was used to determine the energy efficiency by calculating the ratio of the initial energy content in the biomass to the energy loss during pelleting.

$$EE = \frac{IE - ECU}{IE} \cdot 100\% \text{ [%]} \quad (7)$$

where

EE —energy efficiency [%];

IE —initial energy content of biomass [$\text{Wh} \cdot \text{kg}^{-1}$];

ECU —energy consumption unit [$\text{Wh} \cdot \text{kg}^{-1}$].

The energy density of the pellets is a crucial factor to consider in the transportation and storage processes. When the energy density of pellets increases, less space is required for their storage and transportation. This leads to improved efficiency and reduced costs for both the pellet manufacturer and the end user, as noted by Obernberger and Thek [33]. The volumetric energy density can be calculated using Equation (8), which takes into account the measured LHV value and bulk density DB of the pellets.

$$ED = DB \cdot LHV \text{ [GJ} \cdot \text{m}^{-3}] \quad (8)$$

where

ED —energy density [$\text{GJ} \cdot \text{m}^{-3}$];

LHV —lower heating value [$\text{GJ} \cdot \text{kg}^{-1}$];

DB —bulk density [$\text{kg} \cdot \text{m}^{-3}$].

2.12. Emissivity during Pellets Combustion

The test of emissivity during the combustion of the produced pellets was performed on a laboratory stand described in previous publications [34]. The station is equipped with a Moderator Unica VentoEko boiler and a Födisch MCA10 exhaust gas analyzer (Hajnówka, Poland).

The determination of emissivity during pellet combustion was performed in constant settings, i.e., with the following measures:

- air flow of 22%;
- burner power of 19.7 kW;
- fuel flow of $3 \text{ kg} \cdot \text{h}^{-1}$.

The obtained results were normalized to an oxygen (O_2) content of 10% using Equation (9):

$$Z_{s2} = \frac{21 - O_2'}{(21 - O_2'') \cdot Z_{s1}} \text{ [%}, \text{mg} \cdot \text{m}^{-3}] \quad (9)$$

where

Z_{s1} —the actual content of a chemical compound in exhaust gases [%], $\text{mg} \cdot \text{m}^{-3}$];

Z_{s2} —content of a chemical compound in exhaust gases for a given oxygen content [%], $\text{mg} \cdot \text{m}^{-3}$];

O_2' —assumed oxygen content in exhaust gases [%];

O_2'' —actual oxygen content in exhaust gases [%].

3. Results

3.1. Bulk Density of Raw Materials

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

Table 1. The bulk density and ash content.

Raw Material	Bulk Density $\pm$ SD [$\text{kg}\cdot\text{m}^{-3}$]	Ash Content $\pm$ SD [%]
Pine sawdust	122.58 ± 4.35	0.32 ± 0.08
Elderberry waste	427.73 ± 3.82	7.72 ± 0.23

Pine sawdust has a bulk density that is over three times lower than that of elderberry waste ($427.73 \text{ kg}\cdot\text{m}^{-3}$). The tested sawdust has a low ash content of 0.32%, while elderberry waste contains 7.72% of ash. According to the ISO 17225-1:2021-11 standard, the ash content in industrial pellets, depending on the class, may be up to 2% [15]. The addition of elderberry waste will significantly affect the ash content in the wood pellets, but not to an extent that would lead to exceeding the limit specified in the standard.

Due to the need for biomass management, ash content is important for the energy use of biomass. The high contents of macro- and micronutrients may facilitate its use for fertilizer purposes [35].

3.2. Granulometric Distribution of Raw Materials

Table 2 shows the granulometric distribution of the tested pelleted raw materials. The results of the determinations of granulometric distribution show that the fractions with the largest share in pine sawdust are fractions with grain sizes of 4 mm (41.44%), 2 mm (21.82%), and 1 mm (17.81%).

Table 2. Particle size distribution of the tested raw materials.

Raw Material	Fraction Share $\pm$ SD [%]							
	8	4	2	1	0.5	0.25	0.125	0.063
Pine sawdust	1.88 ± 0.09	41.44 ± 2.32	21.82 ± 1.53	17.81 ± 0.54	9.17 ± 0.48	4.54 ± 0.33	2.41 ± 0.52	0.97 ± 0.09
Elderberry waste	0.00	0.00	0.07 ± 0.01	57.13 ± 3.18	32.86 ± 2.11	8.82 ± 1.86	1.09 ± 0.15	0.02 ± 0.01

Elderberry waste is characterized by a granulometric distribution with a much smaller grain size, as the dominant fractions are fraction with grain sizes of 1 mm (57.13%) and 0.5 mm (32.86%). Particles with larger diameters were practically non-existent. Particles with the largest diameters were not found in the elderberry waste, as in sawdust, because they were more fragmented.

3.3. Moisture of Raw Materials

Table 3 shows the moisture contents of the tested raw materials and of the prepared mixtures before pelleting.

Table 3. Moisture of tested raw materials.

Raw Material	Waste Content in the Mixture [%]	Moisture $\pm$ SD [%]
Elderberry waste	10	13.17 ± 0.19 *
	20	14.20 ± 0.23 *
	30	12.75 ± 0.17 *
	100	8.87 ± 0.01
Pine sawdust	100	11.62 ± 0.06
	100	13.34 ± 0.11 *

* moisture content before the agglomeration process (obtained after moistening).

Based on the performed tests, it was found that the moisture content of elderberry waste is 8.87%, while that of sawdust is 11.62%. According to Wróbel et al. [36], the moisture of raw materials is an important parameter influencing the process of pressure agglomeration and the quality of the product. According to the manufacturer of the pelleting line, i.e., TechnoMaszBud (TMB) [37], raw materials with a moisture content below 12% are too dry, which may cause problems during pressure agglomeration. The authors' experience shows that when pelleting sawdust using the SS-5 station (Figure 2), the optimal mixture moisture content is 13%. The tested raw materials are characterized by lower moisture contents, which made it necessary to moisten them until they achieved the specified moisture.

3.4. Elemental Composition of Raw Materials

Table 4 presents the elemental composition of the tested raw materials along with the ash content.

Table 4. Elemental composition of the tested raw materials.

Raw Material	C $\pm$ SD [%]	H $\pm$ SD [%]	N $\pm$ SD [%]	S $\pm$ SD [%]	Cl $\pm$ SD [%]
Elderberry waste	43.59 $\pm$ 0.88	5.48 $\pm$ 0.05	0.89 $\pm$ 0.04	0.03 $\pm$ 0.001	0.0027 $\pm$ 0.0001
Pine sawdust	47.96 $\pm$ 0.11	6.73 $\pm$ 0.02	0.14 $\pm$ 0.02	0.02 $\pm$ 0.001	0.0045 $\pm$ 0.0002

The carbon content depends on the type of plant and the part from which the sample was taken. The tested herbaceous waste from elderberry contained 43.59% of C, while the pine sawdust contained 47.96%. The carbon content in sawdust has been tested numerous times and has been determined as 45–55% [38,39]. In a study conducted by Ward et al. [40], the carbon content in pine chips was 69.2%, while according to Dąbrowska et al. [41], the carbon content in elderberry inflorescences was 49.1%.

The hydrogen content in the tested raw materials was 5.48% in the case of herbaceous waste from elderberry and 6.73% in the case of pine sawdust. The results of a study performed by Zhang et al. [42] showed that the hydrogen content in pine sawdust was 5.2%, while pine needles examined by Font et al. [43] contained 6.5% of hydrogen. The hydrogen content in elderberry inflorescences is much higher than in the tested post-production herbaceous waste from elderberry; in the study conducted by Dąbrowska et al. [41], the hydrogen content was 7.2%.

According to the data in the literature [44,45], the nitrogen content in woody residues and pine sawdust ranges from 0.1% to as much as 6.5%. Compared to the results of the studies discussed above, the tested raw materials are characterized by a low nitrogen content of 0.14% in the case of pine sawdust and 0.89% in the case of herbaceous waste from elderberry. For the EN Plus A2 certificate [15], the maximum nitrogen content in pellets allowed for sale is 0.5%, while for the EN Plus B certificate the maximum nitrogen content is 1%. By analyzing the nitrogen content in the tested raw materials, it can be concluded that the produced pellets, regardless of the added amounts of herbaceous waste from elderberry, qualify for the EN Plus B certificate [15].

The sulfur contained in raw materials may be of natural origin or impurities absorbed by plants. The high sulfur content in the raw materials may indicate high SO₂ air pollution in the places where the trees from which the samples were taken grew. High sulfur content may also accelerate the corrosion of boilers when burning pellets. The tested pine sawdust contained 0.02% S, while in the research conducted by Khalili and colleagues [46], the sulfur content in pine cones was 1.21%. The analyzed elderberry waste contained slightly more sulfur (0.03%) than sawdust. In studies conducted by Dąbrowska and colleagues, the sulfur content in elderberry inflorescences was 0.6% [41].

Analyzing the created elderflower pellets in terms of heavy metals, there were no exceedances of the permissible contents for any of the elements [15]. The chlorine content

in the tested raw materials was 0.0027% in the case of herbaceous waste from elderberry and 0.0045% in the case of pine sawdust.

3.5. Contents of Heavy Metals

The use of various types of post-production waste in the production of biofuels in the form of pellets is widely perceived as an eco-friendly activity that has a positive impact on the environment. One of the most important aspects to determine whether a given type of waste can be considered safe as a biofuel is its chemical composition. For wood pellets, the content of heavy and alkaline metals is regulated by the ISO 17225-1:2021-11 standard [15], which specifies the maximum concentrations of given elements. Table 5 shows the contents of heavy metals in the tested samples.

Table 5. Content of heavy metals in the tested raw materials and pellets.

Material	Content of Heavy Metals $\pm$ SD [mg·kg _{d.m.} ^{−1}]						
	Cr	Ni	Cu	Zn	As	Cd	Pb
Pine sawdust	2.61 $\pm$ 0.22	3.27 $\pm$ 0.07	5.15 $\pm$ 0.45	42.83 $\pm$ 1.65	0.15 $\pm$ 0.02	x $\leq$ 0.05	x $\leq$ 0.05
Elderberry waste	0.00	0.00	7.92 $\pm$ 0.34	53.67 $\pm$ 4.22	1.54 $\pm$ 0.09	0.89 $\pm$ 0.03	6.28 $\pm$ 0.59
Pellets with 10% elderberry waste	2.35 $\pm$ 0.35	2.94 $\pm$ 0.12	5.43 $\pm$ 0.65	43.91 $\pm$ 2.14	0.29 $\pm$ 0.01	0.09 $\pm$ 0.01	0.66 $\pm$ 0.11
Pellets with 20% elderberry waste	2.09 $\pm$ 0.26	2.62 $\pm$ 0.03	5.70 $\pm$ 0.11	45.00 $\pm$ 4.21	0.43 $\pm$ 0.02	0.18 $\pm$ 0.01	1.29 $\pm$ 0.11
Pellets with 30% elderberry waste	1.83 $\pm$ 0.12	2.29 $\pm$ 0.17	5.98 $\pm$ 0.52	46.08 $\pm$ 3.22	0.57 $\pm$ 0.05	0.27 $\pm$ 0.02	1.91 $\pm$ 0.23

The tested pine sawdust is characterized by a low content of heavy metals. The metal present in the largest amount is zinc (42.83 mg·kg_{d.m.}^{−1}). According to Kabata-Pendias [47], zinc content in the environment is usually higher than that of other heavy metals. Similar results were obtained by Bożym et al. [48], who found that zinc content was the highest among the tested heavy metals, amounting to 10.8 mg·kg_{d.m.}^{−1}.

The tested pine sawdust had a chromium content of 2.61 mg·kg_{d.m.}^{−1}, while the samples tested by Bożym et al. [48] contained 2.8 mg·kg_{d.m.}^{−1}. On the other hand, the nickel content was slightly higher, i.e., 3.27 mg·kg_{d.m.}^{−1}, while the samples tested by Bożym et al. [48] contained 1.8 mg·kg_{d.m.}^{−1} of nickel.

Particular attention should be paid to cadmium and lead, which are harmful to the environment. Their contents in the tested pine sawdust were very low, below 0.05 mg·kg_{d.m.}^{−1}. In the study conducted by Aniszewska et al. [49], a high cadmium content in pine seeds was found, amounting to 1.6 mg·kg_{d.m.}^{−1}. However, in the research conducted by Nkongolo et al. [50], a much higher lead content was found in pine branches, at the level of 2.80–8.45 mg·kg_{d.m.}^{−1}.

The contents of copper and arsenic in the tested pine sawdust were 5.15 and 0.15 mg·kg_{d.m.}^{−1}, respectively. According to the ISO 17225-1:2021-11 standard [15], the maximum contents of these metals in wood pellets should be 10 mg·kg_{d.m.}^{−1} in the case of copper and 1 mg·kg_{d.m.}^{−1} in the case of arsenic [15].

No chromium or nickel content was detected in the tested herbaceous waste from elderberry. However, in the research conducted by Sorokopudov et al. [51], a small nickel content, at the level of 0.017 mg·kg_{d.m.}^{−1}, was found in elderberry juice.

As mentioned, the heavy metal found in the greatest amount in herbaceous waste from elderberry was zinc (53.67 mg·kg_{d.m.}^{−1}), and its content was slightly higher than in the tested sawdust. However, Młynarczyk et al. [52] found that elderberries contain 12.4 mg·kg_{d.m.}^{−1} of zinc, with flowers containing three times the amount found in fruits, i.e., 35.2 mg·kg_{d.m.}^{−1}.

The copper content in the tested herbaceous waste from elderberry was 7.92 mg·kg_{d.m.}^{−1}. However, in the research presented by Młynarczyk et al. [52], the contents of this element in flowers and fruits were 11.3 and 5.0 mg·kg_{d.m.}^{−1}, respectively.

The cadmium content in herbaceous waste from elderberry is much higher than in sawdust and amounts to 0.89 mg·kg_{d.m.}^{−1}, while the lead content is 6.28 mg·kg_{d.m.}^{−1}.

According to the ISO 17225-1:2021-11 standard [15], the maximum cadmium and lead contents for wood pellets are 0.5 and 10 mg·kg_{d.m.}^{−1}, respectively [15].

3.6. Heat of Combustion and Heating Value of Raw Materials

Pine sawdust was characterized by slightly higher energy parameters than elderberry waste, with a higher moisture content of 11.62% (Tables 3 and 6). However, it should be noted that the moisture content of both tested raw materials was low, approximately 9–12%.

Table 6. Heat of combustion and heating value of raw materials and pellets.

Material	HHV _{ar} ± SD	HHV _{dry} ± SD	LHV _{ar} ± SD	LHV _{dry} ± SD
	[MJ·kg ^{−1}]			
Elderberry waste	17.52 ± 0.04	19.25 ± 0.05	16.20 ± 0.05	18.00 ± 0.05
Pine sawdust	19.08 ± 0.09	20.27 ± 0.06	17.48 ± 0.08	18.98 ± 0.05
Pellets with 10% elderberry waste	18.92 ± 0.05	20.17 ± 0.05	17.35 ± 0.06	18.88 ± 0.04
Pellets with 20% elderberry waste	18.77 ± 0.06	20.07 ± 0.04	17.22 ± 0.08	18.78 ± 0.03
Pellets with 30% elderberry waste	18.61 ± 0.07	19.96 ± 0.04	17.05 ± 0.09	18.69 ± 0.08

The calorific value of pine sawdust in its dry state was the highest and amounted to 18.98 MJ·kg^{−1}; in the analytical state (analytical moisture 11.62%), it was 17.48 MJ·kg^{−1}. This value is similar to that reported in the literature [53]. In the case of elderberry waste, the dry calorific value was 18.00 MJ·kg^{−1}, while in the analytical state (analytical moisture 8.87%) it was the lowest at 16.20 MJ·kg^{−1}. The literature provides similar LHV values for both tested raw materials. The use of elderberry waste from garden pruning for energy purposes is described in [54], in which it was found that the calorific value of the shoots of this plant is approximately 17.2–17.4 MJ·kg^{−1}. However, in [55], the calorific value of the biomass of invasive herbaceous plants (pine hogweed and giant knotweed) was shown to be above 15.9 MJ·kg^{−1}, which was stated to be applicable to the production of solid biofuels. The calorific value of the pine sawdust used in this study and as a control was similar to that determined in the tests and amounted to 18.6 MJ·kg^{−1}. Other herbal waste presented in the literature, such as chamomile or mint residues, had calorific values similar to that found for elderberry waste. They were 16.7–17.3 MJ·kg^{−1} [56] and 14.8–15.6 MJ·kg^{−1} [57], respectively.

Pellets obtained from pine sawdust and mixtures containing elderberry biomass had a calorific value above 17 MJ·kg^{−1} (Table 6). The highest calorific value was found for pellets made from pine sawdust only (17.48 MJ·kg^{−1}); the lowest was found for pellets with a 30% content of elderberry waste (17.05 MJ·kg^{−1}) (Table 6). The increase in the addition of elderberry waste resulted in decreasing values of this parameter. This is due to the slightly lower calorific value of elderberry biomass. Nevertheless, these are acceptable values, in accordance with the ISO 17225-1:2021-11 [15], at above 16.5 MJ·kg^{−1}, typical for pine wood pellets and higher than for agro-biomass pellets [58,59].

3.7. The Pelletization Process and Characteristics of Pellets

The active power requirement of the granulator for the pressure agglomeration of pine sawdust was 3.41 kW (Figure 3). During the granulation of mixtures containing 10 and 20% elderberry waste addition, the active power demand decreased by about 10% and was 3.05 kW for a mixture containing 10% addition and 3.08 kW for a mixture containing 20% elderberry waste, respectively. The power demand during the agglomeration of the mixture containing 30% waste increased to 3.25 kW (Figure 3). The effect of the addition of elderberry waste parts on the active power demand of the granulator (Ng) during pressure agglomeration of pine sawdust in a flat matrix granulator operating system is described using the following Equation (10):

$$N_g = 0.01z_e + 2.9267 \text{ [kW]} \quad (10)$$

where

N_g —the active power demand of the granulator [kW];

z_e —content of herbaceous waste from elderberry [%].

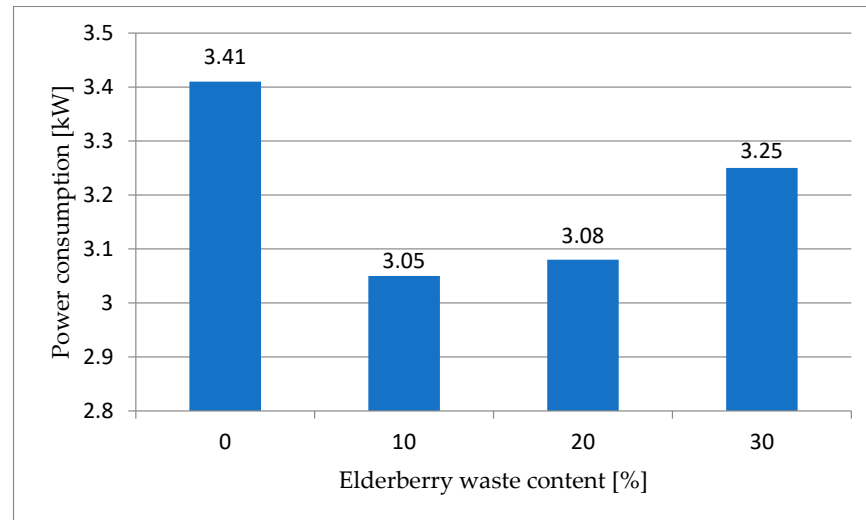


Figure 3. Relationship between the power consumption of the pelletizer and the content of herbaceous waste from elderberry in the mixture.

Čajová Kantová et al. [60], analyzing the energy intensity of pressure agglomeration of spruce sawdust, found that the specific energy consumption was $180.78 \text{ kWh} \cdot \text{t}^{-1}$, while that of beech sawdust was $318.11 \text{ kWh} \cdot \text{t}^{-1}$.

Tumuluru [61], on the other hand, in his study showed a decrease in energy intensity with an increase in the content of pine sawdust in the pelletized mixture of about $90 \text{ kWh} \cdot \text{t}^{-1}$. In his study, he also showed that an increase in the moisture content of the tested mixture increased the specific energy consumption value.

A view of sample pellets made from a mixture of pine sawdust and herbaceous waste from elderberry is shown in Figure 4.

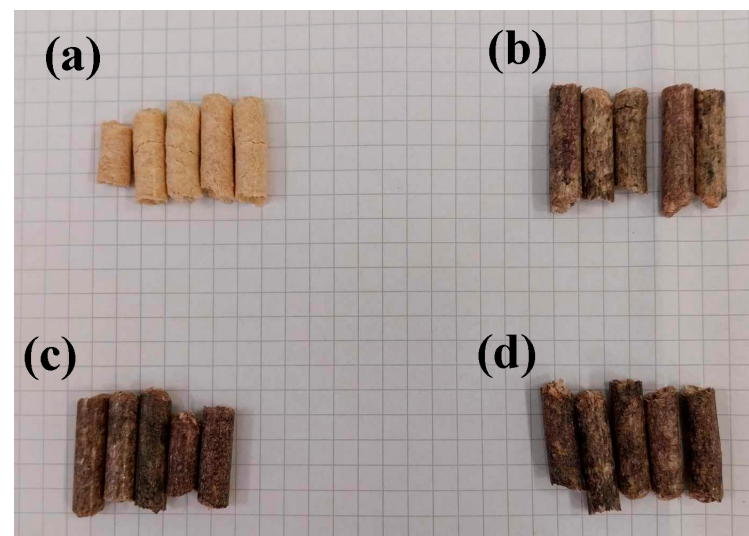


Figure 4. View of pellets made from mixtures of pine sawdust and herbaceous waste from elderberry, added in the amounts of (a) 0%, (b) 10%, (c) 20%, (d) 30%.

3.8. Physical Properties of Produced Pellets

The selected physical properties of the tested pellets are summarized in Table 7. Based on the results obtained, it was found that increasing the addition of elderberry waste from 10 to 30% increases the values of the physical density, bulk density, and kinetic strength of the obtained pellets. This increase is observed at the level of 2.5% for density and about 1% for case bulk density and kinetic durability.

Table 7. Selected physical properties of the tested pellets.

Content of Elderberry Waste Additive [%]	Density $\pm$ SD [kg·m ⁻³]	Bulk Density $\pm$ SD [kg·m ⁻³]	Kinetic Durability $\pm$ SD [%]
0	1231.38 $\pm$ 12.34	652.38 $\pm$ 7.25	98.03 $\pm$ 0.23
10	1236.04 $\pm$ 13.26	649.34 $\pm$ 5.24	98.54 $\pm$ 0.19
20	1249.32 $\pm$ 13.38	654.04 $\pm$ 5.11	99.18 $\pm$ 0.12
30	1263.90 $\pm$ 14.02	658.50 $\pm$ 6.11	99.31 $\pm$ 0.08

A pine sawdust pellet had a density of 1231.38 kg·m⁻³; in a study by Núñez-Retana et al. [62], an oak sawdust pellet had a density of 1256 kg·m⁻³. The addition of elderberry waste to the pelletized sawdust increased the density of the pellet to 1236.04 kg·m⁻³ for a pellet containing 10% of the additive, while a pellet containing 30% was characterized by a density of 1263.90 kg·m⁻³.

The obtained pellets were characterized by a bulk density of over 600 kg·m⁻³, i.e., a value corresponding to the requirements of the ISO 17225-1:2021-11 standard [15]. Stolarski et al. [63] showed that willow pellets may have a bulk density of 584 to 636 kg·m⁻³, while oak pellets have a bulk density of approximately 625 kg·m⁻³.

According to the 17225-1:2021-11 standard [15], pellets should have a kinetic durability of 97.5%. All of the tested samples of the obtained pellets were characterized by higher values of kinetic durability. Research performed by Niedziółka et al. [64] shows that an agglomerate of corn and rapeseed straw, grain and oil waste is characterized by the following kinetic durability values: 86.6% in the case of rapeseed straw pellets, 95.9% in the case of pellets produced from corn straw and wheat bran, and 97.1% for wheat straw pellets. However, research conducted by Rynkiewicz [65] showed that pellets made of pine, cherry, and walnut sawdust have a durability of approximately 98.9%.

3.9. Energy Indicators of Pellet Production

Table 8 presents the results of calculations of the energy indicators for pellet production obtained using Equations (6)–(8).

Table 8. Energy indicators of pellet production.

Indicator	Unit	Pine Sawdust Pellet	Pellet with 10% Elderberry Waste	Pellet with 20% Elderberry Waste	Pellet with 30% Elderberry Waste
HHV	[kJ·kg ⁻¹]	19,080	18,968	18,832	18,672
LHV	[kJ·kg ⁻¹]	17,480	17,363	17,220	17,053
HHV	[Wh·kg ⁻¹]	5300	5269	5231	5187
LHV	[Wh·kg ⁻¹]	4856	4823	4783	4737
Energy consumption unit	[Wh·kg ⁻¹]	68.20	61.00	61.60	65.00
Energy yield of pellets	[Wh·kg ⁻¹]	4788	4762	4721	4672
Energy efficiency	[%]	98.71	98.84	98.82	98.75
Energy density	[GJ·m ⁻³]	11.40	11.27	11.26	11.22

In order to analyze the amount of energy that can be obtained, the energy yield (EY) of pellets was calculated using Equation (7). The relationship between the energy yield of pellets and the energy parameters and characteristics of the process of pelletization is shown in Figure 5.

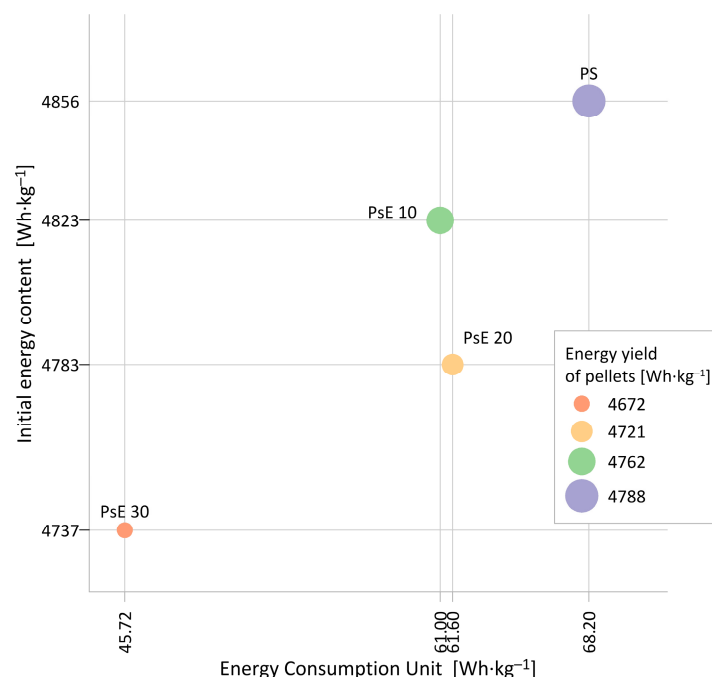


Figure 5. Energy yield of pellets vs. the relationships between the initial energy content and unit energy consumption.

Sawdust pellets were characterized by the highest values of initial energy content; at the same time, their production process was the most energy-intensive. Despite this, the energy yield of these pellets was the highest ($4788 \text{ Wh}\cdot\text{kg}^{-1}$). Increasing the content of elderberry waste resulted in a decrease in the energy consumption of the process and the energy yield. However, increasing the content of black elderberry waste from 10% to 20% slightly reduced the energy demand ($0.6 \text{ Wh}\cdot\text{kg}^{-1}$). The relationship between the energy yield of pellets, their kinetic durability, and pellets' density is presented in Figure 6. Pellets from pine sawdust had the lowest kinetic durability at 98%. However, it should be noted that all the obtained pellets were characterized by high strength, at above 98%. The addition of elderberry waste resulted in an increase in the analyzed parameters (i.e., kinetic durability and pellet density). A further increase in the content of elderberry waste in the mixture resulted in an increase in the kinetic durability and density of the pellets. Hence, from the point of view of EY (energy yield), adding 10% of the tested herbal waste is the most advantageous option, although this did not result in a significant reduction in the energy yield ($26 \text{ Wh}\cdot\text{kg}^{-1}$). However, in order to increase the durability and density of pellets, it is recommended that a higher share, up to 30%, of the additive should be used—taking into account the decrease in EY, by $116 \text{ Wh}\cdot\text{kg}^{-1}$ in this case. The calculated energy yield values were similar to those presented in [66], characterizing the process of pellet production from miscanthus biomass.

The energy efficiency (EE) of the process of pelletization was high (i.e., nearly 99%) in all cases—the differences that occurred were of the order of 0.13%—and no relationship between this parameter and the content of elderberry waste could be found. The energy density (ED), calculated on the basis of the calorific value and the density of pellets was similar, i.e., it was the highest in the case of pellets produced from pine sawdust ($11.40 \text{ GJ}\cdot\text{m}^{-3}$), and decreased with the increase in the content of elderberry waste to $11.22 \text{ GJ}\cdot\text{m}^{-3}$ (for pellets with a 30% elderberry waste content), which gives differences of $0.18 \text{ GJ}\cdot\text{m}^{-3}$ compared to pure sawdust. Garcia et al. [67], examining the process of pelleting wood waste mixed with waste from the agri-food industry, determined the value of this parameter to be between 7.7 and $12.0 \text{ GJ}\cdot\text{m}^{-3}$. Therefore, the ED rates obtained in the study should be considered high. Combined with their high kinetic strength, the high ED value of pellets

results in a reduction in distribution costs as well as losses related to crushing during reloading and transportation.

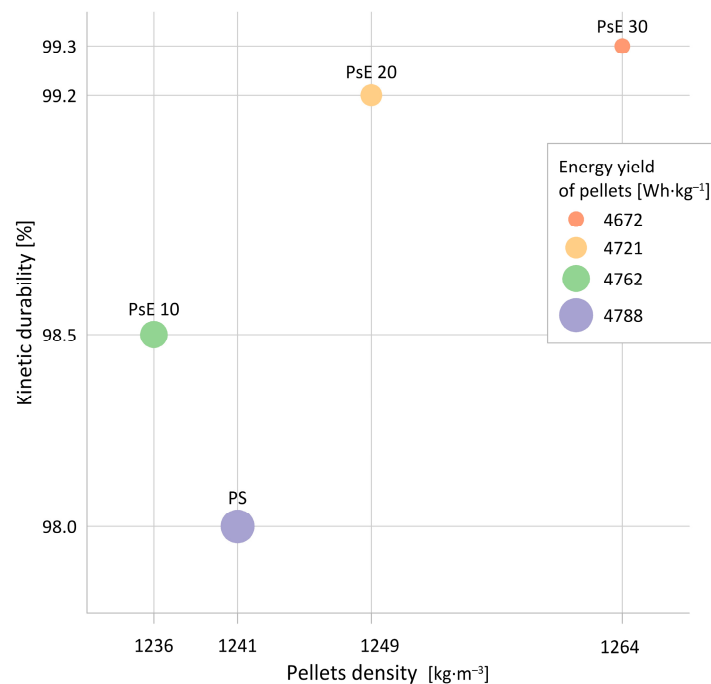


Figure 6. Energy yield of pellets vs. mechanical durability and pellet density.

3.10. The Process of Combustion of Pellets with the Addition of Elderberry Waste

Table 9 shows the results of exhaust gas emissivity from the combustion of pine sawdust pellets with the addition of elderberry waste in the amounts of 10, 20, and 30%. To enable referencing to exhaust emission standards, the results were averaged for 10% O₂ content.

Table 9. Emissivity of exhaust gases from the combustion of pine sawdust pellets with the addition of elderberry waste.

Type of Pellets	Mass Fraction of Additive [%]	Flue Composition at 10% O ₂					λ [-]	Exhaust Gas Temperature at Outlet from Boiler [°C]
		CO ₂ [%]	CO	NO [mg·m ⁻³]	SO ₂	NO _x		
With the addition of elderberry waste	10	10.37	4870.04	157.29	21.48	159.47	4.15	117.33
	20	10.19	8271.49	184.37	24.59	184.42	4.30	124.19
	30	10.01	8881.99	212.72	29.61	212.72	4.42	124.27

An analysis of the obtained results shows that an increase in the addition of elderberry waste results in reductions in CO₂ emissions ranging from 10.37% for pellets with a 10% content of elderberry waste to 10.01% for pellets with a 30% content of elderberry waste.

Controlling the CO content in burned fossil fuels and biofuels is extremely important. The level of CO emissions is a key aspect for assessing both the combustion quality (it is an indicator of the presence of hydrocarbons, soot, dioxins, and furans) and the environmental impact of fuels [68]. The level of CO emissions within the EU is regulated by the Ecodesign standard, which sets the maximum CO emission level at 500 mg·m⁻³ for all boilers, regardless of their purpose and power [69]. The same limits were adopted by the Central Pollution Control Board (CPCB) in 2022, reducing the CO limit from 1200 to 500 mg·m⁻³ [70]. A slightly more liberal approach is adopted in Poland, where boilers with a maximum CO limit of 5000 can be used, and yet new boilers must meet the EU standards [71]. In the case of the tested pellets, each exceeded the CO limit, with an increase in the content of elderberry waste causing an increase in CO emissions. When burning

pellets containing 10% and 30% contents of elderberries, CO emissions were 4870.04 and 8881.99 $\text{mg}\cdot\text{m}^{-3}$, respectively, exceeding the Ecodesign standard set in the Commission Regulation (EU) of 28 April 2015, meaning that the produced pellets do not meet the EU CO standards. To reduce the amount of CO emitted, it is recommended that the oxygen supply during combustion should be increased [69].

According to the Commission Regulation (EU) of 28 April 2015 [69] for class 5 boilers, the NO_x emission limit is 200 $\text{mg}\cdot\text{m}^{-3}$. The tested pellets were characterized by NO_x contents ranging from 157.29 $\text{mg}\cdot\text{m}^{-3}$ (for a 10% content of elderberry waste) to 212.72 $\text{mg}\cdot\text{m}^{-3}$ (for a 30% content of elderberry waste), which means that the produced pellets containing up to 20% of elderberry waste meet the Ecodesign standard in terms of NO_x , while pellets containing 30% of elderberry waste slightly exceed it [69]. In a study by Verma et al. [72], the NO_x content of burnt agro-pellets ranged from 25 to 340 $\text{mg}\cdot\text{Nm}^{-3}$, i.e., values that are at a similar level to those obtained in the present study. According to Paraschiv [73], pellets containing waste from the agro-food industry have higher ash and nitrogen contents, while NO_x emissions are dependent on the nitrogen content of the biomass, which is considered to be inert [73].

In the case of sulfur dioxide emissions, it is low for pellets containing a 10% content of elderberry waste, at 21.48 $\text{mg}\cdot\text{m}^{-3}$. Increasing the addition of elderberry waste from 10 to 30% resulted in a slight increase in SO_2 , to 24.59 $\text{mg}\cdot\text{m}^{-3}$ (at a 20% content of elderberry waste) and 29.61 $\text{mg}\cdot\text{m}^{-3}$ (at a 30% content of elderberry waste). The results obtained by Konieczna et al., who burned pine sawdust pellets, found that the SO_2 contents were 16.39 ppm for 14.06% O_2 , which converts to 27.09 $\text{mg}\cdot\text{m}^{-3}$ for 10% O_2 [74]. The increase in SO_2 content in the samples is undesirable because, of all the gases tested, a high sulfur content is the most undesirable. Sulphur oxides present in the flue gas react with the moisture present in it, leading to the formation of sulfuric acid, which is corrosive, a property which results in faster wear and tear of the plant [75].

The excess air coefficient (λ) increases with an increase in the addition of elderberry waste in pellets from 4.15 for pellets containing 10% of the additive, to 4.42 for pellets containing 30% of the waste. According to Pudlik [76], the value of the λ coefficient depends on the installation and the type of fuel being burned; in the case of biomass, its value is 2.0–2.5. The best combustion effects are obtained in boilers equipped with automatic control of the fuel/air blow ratio, where the λ coefficient is 1.02–1.03 [77].

Analyzing the results obtained from the combustion of pellets with the addition of elderberry waste, it was found that the produced pellets met the applicable standards in terms of SO_2 emissions. In terms of NO_x , pellets containing up to 20% of elderberry waste met the standard [68]. The only gas whose emissions exceed the standards is carbon dioxide, which can have a negative impact on the environment. However, an appropriate selection of combustion parameters can reduce the amount of CO emitted.

4. Conclusions

The following conclusions can be drawn from the study of pressure agglomeration of pine sawdust with the addition of herbaceous waste from elderberry:

1. The addition of elderberry waste to the compacted mixture with pine sawdust had a positive effect on the density and bulk density of the obtained pellets. Increasing the content of elderberry waste in the compacted mixture from 10 to 30% resulted in an increase in the density of the pellets from 1236.04 to 1263.90 $\text{kg}\cdot\text{m}^{-3}$ and an increase in the bulk density from 649.34 to 658.50 $\text{kg}\cdot\text{m}^{-3}$. The obtained pellets met the ISO 17225-1:2021-11 standards [15], according to which the minimum bulk density of industrial pellets should be higher than 600 $\text{kg}\cdot\text{m}^{-3}$.
2. All the produced pellets had a very high kinetic strength of $x \geq 98.5\%$. Increasing the content of elderberry waste in the compacted mixture from 10 to 30% resulted in an increase in the kinetic strength of the pellets from 98.54 to 99.31%. The obtained results meet the kinetic strength requirements of ISO 17225-1:2021-11. The produced

pellets can be classified in the highest pellet class (L_1), for which the minimum kinetic strength is 97.5%.

3. The addition of elderberry waste resulted in a decrease in the active power requirement of the pelletizer from 3.41 kW (for pelletization of pine sawdust alone) to 3.05 kW (for pelletization of the mixture containing 10% of elderberry waste). Increasing the content of elderberry waste in the compacted mixture from 10 to 30% increased the power requirement to 3.25 kW.
4. The chemical analysis showed that the resulting pellets had a low heavy metals content, relative to the requirements of ISO 17225-1:2021-11.
5. The energy efficiency of the process of pelletizing pine sawdust and mixtures containing elderberry biomass was found to be very high, at above 98%. The addition of elderberry waste to pine sawdust led to a decrease in energy consumption during the process of pelletization. However, it also resulted in a decrease in the energy yield, due to the lower calorific value of elderberry waste. Its use as an additive had a positive effect on kinetic durability and pellet density, leading to an increase in these parameters. In order to obtain the highest energy yield, it is recommended that a 10% content of elderberry waste should be used. On the other hand, in order to increase the durability and density of pellets, a larger amount of the additive can be used. It is also worth noting that the pellets have a high ED index, which, when combined with their high kinetic strength, can help to reduce losses and transport costs.
6. The flue gas emissivity test showed a negative effect of the addition of elderberry waste on CO emissions. The level of CO emissions increased significantly with increasing waste addition in the pellets, reaching $8881.99 \text{ mg}\cdot\text{m}^{-3}$ (for pellets containing 30% of elderberry waste). Consequently, the obtained pellets did not meet the CO emission standards set out in the Commission Regulation (EU) of 28 April 2015. On the other hand, SO_2 emissions during the combustion of all the tested pellets were at a low level, between 21.48 and $29.61 \text{ mg}\cdot\text{m}^{-3}$. NO_x emissions met the emission standards (stipulating a limit of $200 \text{ mg}\cdot\text{m}^{-3}$) in the case of pellets containing 10% and 20% of elderberry waste, while during the combustion of pellets containing 30% of the additive, this value was minimally exceeded and amounted to $212.72 \text{ mg}\cdot\text{m}^{-3}$.

Based on the results of the study, it can be concluded that herbaceous waste in the form of elderberry parts has a great potential for use during the process of pressure agglomeration of pine sawdust, improving the physical properties of the finished product.

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