

Article

Effect of Plum Seeds and Rosin Adding to Sawdust on the Pelletisation Process and Fuel Pellet Quality

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Abstract

This study investigates the influence of crushed plum stones and rosin (colophony) as additives in the pelletisation of pine sawdust, with a focus on energy consumption, pellet quality, and combustion performance. The addition of crushed plum stones combined with 10% rosin reduced the energy demand of the process. Incorporating 10–20% plum stones with 10% rosin decreased the pelletiser power demand by 18% and 25%, respectively, compared to pure sawdust. Plum stone addition significantly improved the energetic parameters of pellets. At a 20% share, the calorific value increased to $18.02 \text{ MJ} \cdot \text{kg}^{-1}$ and the heat of combustion to $20.04 \text{ MJ} \cdot \text{kg}^{-1}$, while 10% rosin further enhanced these values by $1.67 \text{ MJ} \cdot \text{kg}^{-1}$ (8.4%). Although bulk and particle density slightly decreased, a 10% plum stone share raised the kinetic strength to 97.24%, indicating improved mechanical durability. Combustion tests confirmed favourable properties of the modified pellets, including lower air excess coefficients (λ) and reduced emissions of CO, NO, and SO₂. However, a 10% rosin content slightly exceeded CO emission limits set by the Ecodesign Directive, suggesting that its share should be reduced to ~5%. The results confirm that crushed plum stones and rosin are effective modifiers in sawdust pelletisation, enhancing both process efficiency and fuel quality. This approach supports circular economy principles by converting plant-based residues into high-quality biofuels.

Keywords: fuel pellets; sawdust; waste; plum stones



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1. Introduction

The progressive degradation of the environment and the increasing deficit of natural resources represent some of the most pressing challenges of the modern world. Unsustainable exploitation of environmental components—particularly soils, water, and the atmosphere—combined with the transformation of natural ecosystems, has led to a decline in both the quality and availability of these resources [1]. Key anthropogenic drivers of this phenomenon include excessive resource extraction, deforestation, and the intensification of land use for agricultural production. The consequences of environmental degradation and the depletion of natural resources are global in scope and long-term in nature [2].

The limited availability of natural resources, coupled with growing global energy demand and rising costs of conventional energy production methods, necessitates the identification of new energy solutions [3]. In response, sustainable and forward-looking

energy pathways based on the utilisation of locally available renewable raw materials have attracted increasing scientific and industrial interest. Among these, biofuels derived from non-petroleum feedstocks—such as pellets produced from waste biomass—offer an efficient and environmentally friendly alternative within the energy sector [4,5].

The agricultural and food sectors most frequently produce waste such as potato pulp from starch production, buckwheat husks from groat milling, rapeseed cake from oil extraction, and herbal residues from the drying, packaging, and sorting of herbs. Such residues are often underutilised and pose a significant disposal challenge for processing facilities [6]. The uncontrolled decomposition of agricultural and agri-food industry (AAI) wastes generates substantial amounts of pollutants, including hazardous compounds. Consequently, the development of new, rational technologies for the processing of these by-products is urgently required [7,8].

AAI-derived residues can be valorised through multiple pathways. The most common conversion methods include combustion for energy production (characterised by low efficiency and limited energy value) [9], composting (a time-consuming process yielding a product of limited utility) [10], and use as animal feed [11]. More advanced valorisation strategies involve the extraction of bioactive compounds and bioconversion processes, which enable the use of waste as a feedstock for the production of a wide spectrum of high-value products, including food additives, cosmetics, functional materials, biopolymers, and biofuels [12]. Such approaches not only generate additional revenues from secondary raw materials but also promote the retention of carbon in organic form, thereby reducing CO₂ emissions and contributing to the principles of a sustainable circular economy.

One promising method of managing plant-based residues is their densification into pellets or briquettes through pressure agglomeration, as confirmed by numerous studies [13–16]. While wood-based waste is the most common feedstock, recent research increasingly focuses on alternative sources such as fruit and vegetable processing residues.

Civitarese et al. [17] investigated the potential of spent coffee grounds and their mixtures with sawdust as alternative bioenergy sources. Their findings demonstrated that the addition of coffee residues negatively affected the physical properties of pellets, particularly their mechanical durability and bulk density. However, significant environmental benefits were observed, including reductions in ash content (up to 30%) and nitrogen content (over 50%), which may considerably decrease combustion-related emissions. Pellets containing 50% coffee grounds and 50% sawdust achieved an acceptable nitrogen content of 1.96%, although increased coffee residue levels were associated with reduced pellet durability, limiting their commercial applicability.

Lajili et al. [18] produced and combusted pellets from four different mixtures of pine sawdust and olive mill solid residues at an initial moisture content of ~20%. Their results indicated promising combustion efficiency and emission characteristics. Rahaman [19] reported that in a manually operated piston-press cold densification system, a pressure of 34.5 MPa was sufficient to produce briquettes of satisfactory quality from rice grass with added sawdust as a binder. Ferreira et al. [20] produced and characterised pellets from residual biomass originating from the processing of *Dinizia excelsa*, *Manilkara elata*, and *Eucalyptus* spp. sawn wood, finding that all tested compositions complied with international quality standards for export.

Matkowski et al. [21] pelletised wheat straw and its mixtures with cassava starch or calcium carbonate (with tests carried out in an open-chamber die, where the orifice diameter measured 8 mm and the chamber height was adjusted to 66, 76, and 86 mm) to determine optimal pelleting conditions. Their study demonstrated that the density of wheat straw pellets was maximised with the addition of 4% cassava starch or calcium carbonate. Chojnacki et al. [22] examined the effects of adding fruit pomace and vegetable residues to

barley straw on pellet hardness, density, ash content, and calorific value, concluding that such residues improved the quality of straw pellets.

Chen et al. [23] investigated the role of wet fermented soybean sludge in the pelletisation of corn straw. Their results indicated improved pellet quality, reduced energy demand, and lower specific energy consumption of forming equipment with the inclusion of soybean sludge. Njuguna et al. [24] pelletised baobab fruit residues (fruit shells and press cake), both separately and as mixtures, using a manually constructed hydraulic press, and analysed their physicochemical characteristics. In addition, the influence of moisture content and blend ratios on pellet characteristics—such as bulk density, Higher Heating Value (HHV), and Pellet Durability Index (PDI)—was evaluated.

The north-eastern region of Poland is characterised by the predominance of industries related to agriculture, agri-food processing, and wood processing. As a result, these sectors generate large amounts of various types of production residues, including wood waste, rosin by-products, and fruit processing residues such as crushed plum stones. According to environmental regulations, these materials must be either utilised or disposed of appropriately.

The aim of this study was to assess the suitability of these waste streams for the production of solid biofuels in the form of pellets and to determine optimal blending ratios that would not deteriorate, and potentially improve, selected fuel properties compared to conventional wood-based pellets. This approach addresses several key challenges simultaneously: it provides a sustainable utilisation pathway for agri-food residues that would otherwise be destined for disposal, partially alleviates the limited availability of wood residues on the market, and aligns with the principles of the circular economy, sustainable development, and waste impact reduction.

An additional advantage of this strategy is the potential to lower the production costs of solid biofuels by incorporating readily available agricultural and wood processing residues, while at the same time improving the energy performance of the produced pellets and enhancing the overall resource efficiency of the industries that generate these by-products.

The specific aim of the research presented herein was to determine the influence of plum seed and rosin additions (in proportions ranging from 0% to 20%) on the pelletisation process of pine sawdust, as well as to evaluate the quality of the resulting biofuel. Experimental results enabled the identification of optimal additive levels that ensured favourable physical properties (particularly mechanical durability) alongside desirable energy parameters of the pellets.

2. Materials and Methods

2.1. Materials

The primary raw material used in the study consisted of wood waste, including sawdust, shavings, and offcuts, which were generated during production at the PPUH TARPOL Władysław Żero facility (Poplawy, Poland).

During the experimental procedure, ground plum stones, obtained from the Fruit and Vegetable Processing Plant in Lubawa, were incorporated. In addition, a 10% proportion of comminuted rosin was introduced as an additive.

2.2. Determination of Moisture Content

Quantification of the raw materials' moisture content was performed in accordance with the ISO 18134-1:2015-11 standard [25]. An AXIS AGS moisture analyser was utilised for these measurements. To ensure accuracy and representativeness, five independent tests

were carried out for each material at a controlled temperature of 105 °C. The final moisture content was then established as the arithmetic mean of these five acquired results.

2.3. Determination of Ash Content

The ash content of the raw materials was determined following the PN-EN ISO 18122:2023 standard [26]. This procedure involved incinerating the samples in a muffle furnace at a temperature of 815 ± 15 °C until complete combustion of the organic matter was achieved. Each measurement was performed in three replicates to ensure the reliability of the results. The ash content was determined on a dry basis. Subsequently, the residual inorganic material (ash) was weighed, and the ash content was calculated 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 both raw materials and pellets was assessed in accordance with PN-EN ISO 17828:2016-02 [27]. The measurement was carried out by filling a container of known volume (internal diameter: 167 mm; internal height: 228 mm) with the tested material. Each determination was performed in three replicates to ensure measurement repeatability. Bulk density was calculated as the ratio of the sample mass—determined using an OHAUS AX224M analytical balance (Nänikon, Switzerland) with a precision of ± 0.1 mg—to the container volume.

2.5. Determination of Particle Size Distribution

The granulometric distribution of the samples was assessed in accordance with the PN-R-64898:2009 standard [28]. This analysis was conducted using an LPz-2e laboratory sieve shaker (Multiserv Morek, Marcyporeba, Poland), which features a vibrating base and a stack of sieves with mesh sizes of 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm. Each analysis was performed in three replicates to ensure the reliability and repeatability of the granulometric data.

2.6. Elemental Composition Analysis

The carbon, hydrogen, nitrogen, and sulfur (CHNS) content was analysed following the procedures outlined in PN-EN ISO 16948:2015-07 [29] and PN-EN ISO 16994:2016-10 [30]. Measurements were conducted using a LECO CHN628 elemental analyser (St. Joseph, MI, USA) equipped with sulfur detection capability. Each analysis was performed in three replicates, and the results were reported on a dry basis.

2.7. Determination of Calorific Value and Heat of Combustion

The calorific value (HHV) and the heat of combustion (LHV) were determined in accordance with PN-EN ISO 1928:2002 [31] and based on methodologies previously reported in the literature [5,32]. Each measurement was performed in five replicates to ensure accuracy and statistical reliability. These parameters were calculated using Equation (2), which incorporates the previously measured contents of moisture, ash, hydrogen, and sulphur. In particular, the moisture-corrected calorific value (Q_i^a) was calculated according to the following Equation (2) [33]:

$$Q_i^a = Q_s^a - 24.43(w + 8.94H^a) \quad (2)$$

where

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

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

w —moisture content of the sample [%],

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

24.43—coefficient accounting for the heat of water vaporisation 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

Following the determination of the physical and chemical properties of the examined materials, mixtures were formulated using pine sawdust, post-production plum stones and 10% of crushed rosin. A fixed rosin content of 10% was selected based on preliminary trials, which indicated that this proportion provided a good balance between mechanical properties, process stability, and energy characteristics. Crushed plum stones were incorporated at proportions of 10%, 15%, and 20% by weight. Each blend was moistened to achieve a target moisture content of 16%, then transferred into dedicated sealed containers. The materials were thoroughly mixed and subsequently stored for 24 h under airtight conditions to minimise water loss through evaporation.

The prepared mixtures were subjected to pelletisation using the SS-5 station, which is based on the TechnoMaszBud Prime200 pelletiser (Szupno, Poland). The device is powered by a 12 kW electric motor operating at a rotational speed of 1440 rpm. The pelletising mechanism consists of a flat, stationary die and two counter-rotating rollers that compress the material through the matrix openings to form cylindrical pellets. A detailed description of the position can be found in the articles [5,34].

The constant values during the research were as follows:

- $w_m = 16$ —mixture humidity [%],
- $z_k = 10$ —content of crushed rosin [%],
- $d_o = 6$ —diameter of holes in the matrix [mm],
- $d_m = 216$ —diameter of the matrix [mm],
- $h_m = 32$ —height of the matrix [mm],
- $Q_m = 50$ —mass flow rate of the mixture [$\text{kg} \cdot \text{h}^{-1}$],
- $n_r = 124$ —rotational speed of the compaction roller system [rpm],
- $h_r = 0.2$ —gap between the rollers and the matrix [mm].

2.9. Physical Properties of Pellets

2.9.1. Density of Pellets

The density of the produced pellets was determined by selecting a representative sample of 10 pellets. To ensure accurate dimensional measurements, the edges of these selected pellets were carefully smoothed using an EINHELL WSG-125E angle grinder (Landau, Germany). Following preparation, each pellet's dimensions were measured using a calliper with a precision of 0.05 mm. Subsequently, the mass of each pellet was determined using an analytical balance with an accuracy of ± 0.001 g. The physical density ρ_g for each pellet was then calculated from its measured mass and dimensions using Equation (3):

$$\rho_g = \frac{m_g}{V_g} \quad (3)$$

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):

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

where

r —radius of pellets [m],

h —height of pellets [m].

2.9.2. Bulk Density of Pellets

The bulk density of the pellets was assessed in accordance with the PN-EN ISO 17828:2016-02 standard [27]. Pellets were loaded into a container with a predetermined volume until it was adequately filled. The total mass of the filled container was then measured using an analytical balance with a precision of ± 0.1 mg. The bulk density was subsequently calculated as the quotient of the pellet mass and the container's volume.

2.9.3. Determination of the Kinetic Strength of the Pellets

The mechanical durability of the produced pellets was evaluated following the PN-EN ISO 17831-1:2016-02 standard [35], with additional methodological details from previous studies [36]. The Holmen NHP100 durability tester (Norfolk, UK) was employed for this assessment. Prior to testing, the pellet sample was pre-screened using a 5 mm sieve to eliminate any pre-existing fines. A standardised 100 g sample was introduced into the test chamber where pellets were subjected to repeated impacts through an air stream system that caused collisions between the pellets and the chamber's perforated surfaces. Following the test cycle, the sample underwent secondary sieving, and the remaining intact pellets were quantified by weight. The kinetic durability index 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 —sample weight before test [kg],

m_2 —sample weight after test [kg].

The constant values during the research were as follows:

- $T = 60$ —duration of the test [s],
- $p = 7$ —target pressure [kPa].

2.10. Research on Pellet Combustion and Determination of Exhaust Gas Composition

The emissivity characteristics during pellet combustion were evaluated using a laboratory setup previously described in the literature [37]. The experimental station comprised a Moderator Unica VentoEko boiler system coupled with a Födisch MCA10 exhaust gas analyser (Markranstädt, Germany) for comprehensive emissions monitoring.

The combustion tests were conducted under strictly controlled conditions:

- Air flow rate: 22% (of maximum capacity),
- Burner power output: 19.7 kW,
- Fuel feed rate: $3 \text{ kg}\cdot\text{h}^{-1}$.

To ensure comparability with standard reference conditions, all measured emissivity values were normalised to a standardised oxygen concentration of 10% using Equation (6) [37]:

$$Z_{s2} = \frac{21 - O_2'}{(21 - O_2'') \cdot Z_{s1}} \quad (6)$$

where

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

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

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

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

3. Results

3.1. Moisture Content of the Analysed Raw Materials

Table 1 presents the results of the moisture content analysis for the raw materials used in the study, namely pine sawdust, plum stones, and rosin.

Table 1. Moisture content of the analysed raw materials.

Raw Material	Moisture $\pm$ SD [%]
Pine sawdust	13.52 ± 0.22
Plum stones	14.32 ± 0.19
Rosin	0.33 ± 0.02

Based on the conducted measurements, it was found that the pine sawdust used in the study exhibited a moisture content of 13.52%, plum stones 14.32%, and rosin 0.33%. According to the technical specifications of TechnoMaszBud (TMB) [38], the manufacturer of the pellet production line, raw materials with a moisture content below 12% exhibit insufficient plasticity, which may result in operational difficulties during the pelleting process. Based on experimental observations conducted with the SS-5 pelleting station, the research team determined that a moisture content of 13% was too low for pelleting mixtures based on sawdust. Consequently, it was necessary to adjust the moisture content of the mixtures to the target level of 16% prior to pelleting.

3.2. Granulometric Distribution of Sawdust and Crushed Plum Stones

Table 2 presents the granulometric distribution of the raw materials used in the study.

Table 2. Granulometric distribution of the raw materials used in the study.

Raw Material	Fraction Share [%]								
	8	4	2	1	0.5	0.25	0.125	0.063	<0.063
Pine sawdust	1.063	22.707	30.625	31.813	10.511	2.387	0.535	0.09	0.015
Plum stones	0.00	0.237	27.399	41.586	15.546	8.668	5.798	0.288	0.012

The results of the granulometric analysis (Table 2) indicate that, in the pine sawdust samples, the fraction of 1.00 mm exhibited the highest percentage share (31.813%). Slightly lower shares were observed for the 2.00 mm fraction (30.625%), the 4.00 mm fraction (22.707%), and the 0.50 mm fraction (10.511%). The smallest percentage share, amounting to 0.015%, was attributed to the oversize fraction of <0.063 mm.

In the analysed plum stone samples, the 1.00 mm fraction also accounted for the largest percentage share (41.586%). This was followed by the 2.00 mm fraction (27.399%) and the 0.50 mm fraction (15.546%). Minor contributions were recorded for the 4.00 mm fraction (0.237%) and the 0.063 mm fraction (0.288%). The smallest share, 0.012%, was again observed for the oversize fraction <0.063 mm.

3.3. Bulk Density of the Tested Raw Materials

Table 3 presents the results of the bulk density measurements of the raw materials employed in the experimental investigations.

Table 3. The bulk density and ash content.

Raw Material	Bulk Density $\pm$ SD [$\text{kg}\cdot\text{m}^{-3}$]	Ash Content [%]
Pine sawdust	80.07 ± 1.17	1.05 ± 0.12
Plum stones	547.55 ± 6.01	0.85 ± 0.08
Rosin	561.02 ± 3.015	-

Based on the experimental results (Table 3), it can be observed that the tested pine sawdust exhibited a relatively low bulk density of approximately $80 \text{ kg}\cdot\text{m}^{-3}$. In contrast, the ground plum stones reached a bulk density of about $547 \text{ kg}\cdot\text{m}^{-3}$, while the ground rosin added to the sawdust showed a bulk density of approximately $561 \text{ kg}\cdot\text{m}^{-3}$.

3.4. The Pelleting Process of a Mixture of Sawdust, Crushed Plum Stones, and Rosin

Table 4 presents the results of the investigation into the effect of incorporating crushed plum stones into a sawdust mixture, with an additional 10% share of rosin. The study assessed the influence of plum stone content on the pelleting process, expressed as the power demand of the pelletiser during the compaction of the sawdust–rosin mixture, as well as on the mechanical durability, bulk density, and particle density of the produced pellets.

Table 4. Results of the study on the influence of crushed plum stone content in a pine sawdust mixture on the pelleting process (pelletiser power demand), mechanical durability, particle density, and bulk density of the produced pellets.

Parameter	Plum Stone Content [%]				ISO 17225-1:2021-11 [39]	
	0	10	15	20	Class A	Class B
Kinetic strength $\pm$ SD [%]	92.84 ± 0.31	97.24 ± 0.28	96.77 ± 0.33	93.06 ± 0.12	≥ 96.0	≥ 95.0
Density of pellets $\pm$ SD [$\text{kg}\cdot\text{m}^{-3}$]	1293.87 ± 13.51	1225.37 ± 21.02	1209.94 ± 23.19	1193.94 ± 14.82	-	-
Bulk density $\pm$ SD [$\text{kg}\cdot\text{m}^{-3}$]	632.81 ± 6.28	556.37 ± 8.11	536.25 ± 5.48	495.21 ± 6.63	≥ 600	≥ 550
Pelletiser's power demand $\pm$ SD [kW]	3.86 ± 0.11	3.54 ± 0.19	3.12 ± 0.09	2.91 ± 0.13	-	-

Figure 1 shows a view of the granulate obtained from sawdust and from a mixture of sawdust with various contents of crushed plum stones and with 10% of crushed rosin.

3.4.1. Effect of Plum Stones and Rosin on the Power Demand of the Pelletiser During the Pelleting of Pine Sawdust

Figure 2 presents the results of the study on the influence of crushed plum stone content in a mixture of pine sawdust with a 10% share of rosin on the course of the pelleting process. The results are expressed as the power demand of the pelletiser recorded during the compaction of the pine sawdust mixture.

Based on the obtained results (Table 4, Figure 2), a significant effect of the crushed plum stone content in the sawdust mixture with an additional 10% share of rosin on the pelletiser power demand was observed.

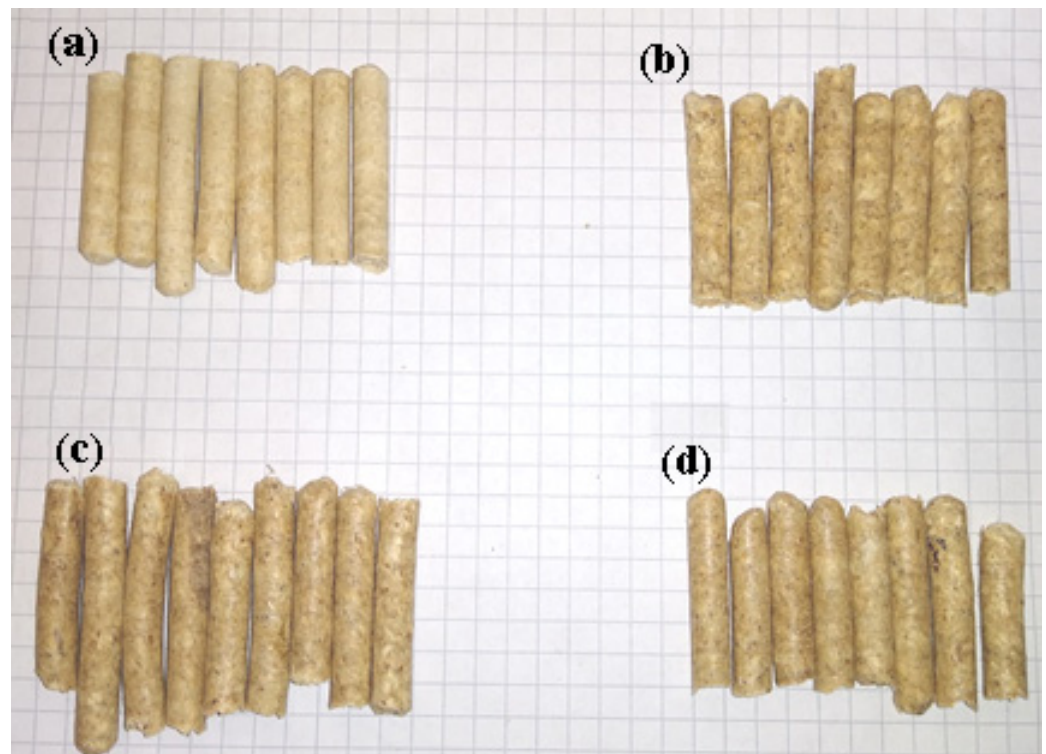


Figure 1. View of the granulate obtained from a mixture of pine sawdust with varying content of crushed plum stones: (a) 0%, (b) 10%, (c) 15%, and (d) 20%.

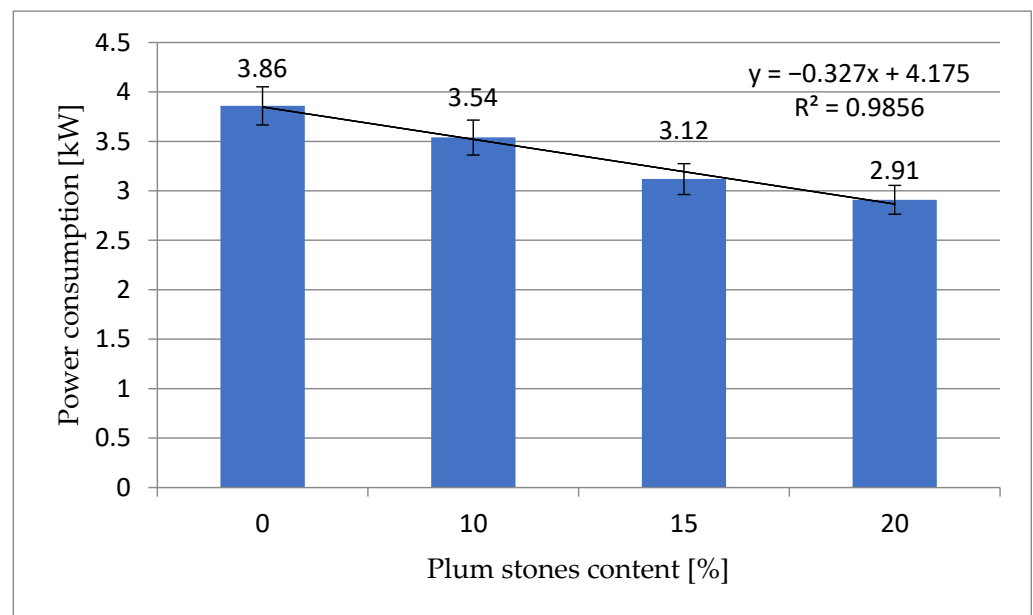


Figure 2. Pelletiser power demand as a function of plum stone content. Bars represent mean $\pm$ SD. The black line shows the linear regression fit ($R^2 = 0.986$).

An increase in the content of crushed plum stones from 10% to 20% (at a mixture moisture level of approximately 16%) resulted in a reduction in the pelletiser power demand by about 18% (from 3.54 kW to 2.91 kW), and by approximately 25% (from 3.86 kW to 2.91 kW) compared to the densification of pure sawdust.

The conducted investigations demonstrated that the addition of crushed plum stones together with 10% rosin to the sawdust mixture significantly enhanced the compressibility

of the tested material. This is evidenced by the substantial decrease in pelletiser power demand with increasing plum stone content and the presence of the rosin additive.

The influence of crushed plum stone content in the sawdust mixture on the pelletiser power demand N_g is described by the following Equation (7):

$$N_g = -0.327Z_s + 4.175 \quad (7)$$

where

N_g —granulator power requirement [kW],

Z_s —content of crushed plum stones [%].

As reported by Sarfraz et al. [40], improving energy efficiency is considered one of the most effective, and at the same time, environmentally friendly solutions for meeting global energy demands. According to Ghalandari and Iranmanesh [41], minimising both coarse and very fine particle fractions plays a crucial role in reducing energy consumption.

Maj et al. [42] investigated the energy demand of the pelleting process for agricultural residues, including maize cobs, husks, and kernels. Depending on the composition of the mixture, the specific energy consumption of the pressure agglomeration process ranged from 47.6 to 78.6 Wh·kg^{−1}. Skonecki and Portręć [43] demonstrated a positive effect of moisture content on the pressure agglomeration of lignocellulosic biomass (miscanthus, prairie cordgrass, and Virginia mallow). They reported that the moisture level of the agglomerated mixture had a pronounced impact on its compressibility and the overall agglomeration process. Adjusting the moisture content from 10% to 22% was shown to reduce the energy demand of the process by up to 14.7%. In turn, Mashek et al. [44] reported that the type of sawdust used for pelleting significantly influences the energy requirements. Their study showed that the energy consumption for pine sawdust pelleting was 9.5 kWh·t_{DW}^{−1}, whereas for birch sawdust, the value was substantially lower at 6.6 kWh·t_{DW}^{−1}.

3.4.2. Mechanical Durability of the Pellets

Based on the conducted experiments (Table 4), it was found that increasing the proportion of crushed plum stones in the sawdust mixture from 10% to 20% resulted in a slight decrease in the mechanical durability of the pellets by approximately 4% (from 97.24% to 93.06%). The durability of pellets containing 10% crushed plum stones was slightly higher compared to pellets produced solely from sawdust (with the same moisture content of 16%), which reached 92.84%.

Mechanical durability is among the most critical quality parameters of pellets [45]. According to ISO 17225-1:2021-11 [39], high-quality fuel pellets should exhibit a mechanical durability of at least 97.5%. Miranda et al. [46] reported that most biomass pellets demonstrate durability values above 95%.

In studies conducted by Wattana et al. [47], pellets produced from cajuput leaves and teak sawdust showed slightly lower durability levels, ranging between 87.64% and 96.76%. According to Masche et al. [48], pellets manufactured from pine sawdust exhibited a durability of 98.5%, whereas those from beech sawdust reached 96.7%. Similar results were obtained by Monedero et al. [49], who reported a durability of 97.8% for pine pellets.

3.4.3. Particle Density and Bulk Density of the Pellets

Figure 3 presents the results of the study on the influence of crushed plum stone content in a sawdust mixture with the addition of 10% ground rosin on the particle density (Figure 3) and bulk density (Figure 4) of the produced pellets.

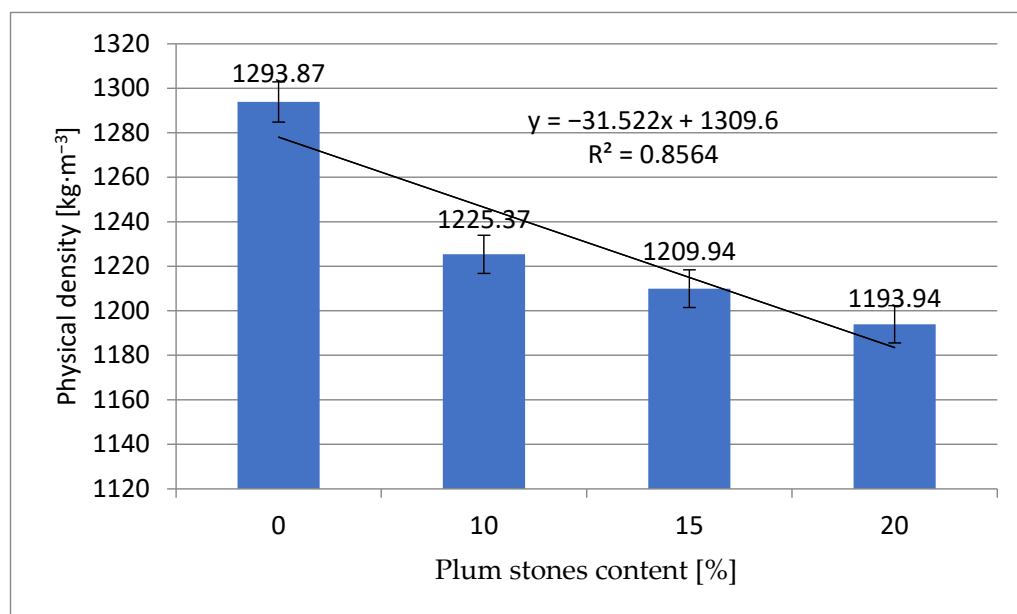


Figure 3. The effect of the content of crushed plum stones in the mixture with sawdust and rosin on the physical density.

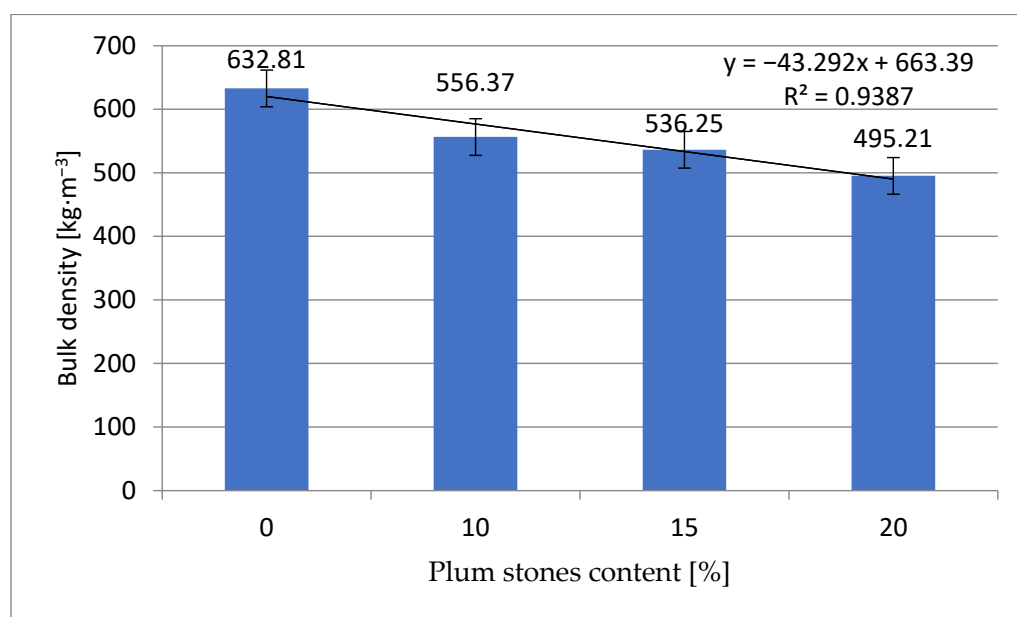


Figure 4. The effect of the content of crushed plum stones in the mixture with sawdust and rosin on the bulk density.

Based on the conducted investigations (Figure 3), it was found that increasing the content of crushed plum stones in the pine sawdust mixture from 10% to 20% led to a decrease in pellet density from 1225.37 kg·m⁻³ to 1193.94 kg·m⁻³. At each level of plum stone addition, the produced pellets exhibited slightly lower densities compared to pellets obtained from pure sawdust (with the same moisture content of 16%), which reached 1293.87 kg·m⁻³. Comparable values for wood pellets produced from oak sawdust were reported by Núñez-Retana et al. [50], who obtained a particle density of 1256 kg·m⁻³.

Significantly higher particle density values for sawdust pellets were reported by Horabik et al. [51]. Their study presented particle densities of 1468.7 kg·m⁻³ for pine sawdust pellets, 1459.9 kg·m⁻³ for oak sawdust pellets, and 1465.3 kg·m⁻³ for birch

sawdust pellets. In contrast, pellets produced from maize and rice straw were characterised by slightly lower particle densities, averaging around $1220.02 \text{ kg}\cdot\text{m}^{-3}$ [52].

A similar trend to that observed for particle density was found for the bulk density of the pellets as a function of the crushed plum stone content in the sawdust mixture. In this case, increasing the proportion of crushed plum stones from 10% to 20% led to a reduction in bulk density from $556.37 \text{ kg}\cdot\text{m}^{-3}$ to $495.21 \text{ kg}\cdot\text{m}^{-3}$ (Figure 4).

According to ISO 17225-1:2021-11 [39], pellets intended for energy purposes should exhibit a bulk density above $600 \text{ kg}\cdot\text{m}^{-3}$. Among the produced pellets, this requirement was met only by those without plum stone addition. Relative to the standard, the poorest result was obtained for pellets containing 20% plum stones and 10% rosin, with a bulk density of $495.21 \text{ kg}\cdot\text{m}^{-3}$.

Horabik et al. [51] investigated the effect of moisture and compaction pressure on the physical properties of pellets produced from various sawdust types. Pellets manufactured from pine sawdust at 8% moisture and compacted under 60 MPa exhibited a bulk density of $779.6 \text{ kg}\cdot\text{m}^{-3}$. Increasing the pressure to 120 MPa resulted in an increase in bulk density to $937.8 \text{ kg}\cdot\text{m}^{-3}$. However, higher initial moisture content had a negative effect. Raising the moisture of the agglomerated mixture to 20% caused a decrease in bulk density to 610.9 and $673.1 \text{ kg}\cdot\text{m}^{-3}$, respectively.

Santos et al. [53] studied pressure agglomeration of residues from the furniture industry. Pellets made from Paraná pine, Brazilian pine, and candelabra tree residues showed a bulk density of $540.9 \text{ kg}\cdot\text{m}^{-3}$. Carbonisation of the pellets reduced bulk density depending on the process temperature, with values as low as $349.0 \text{ kg}\cdot\text{m}^{-3}$. Niedziółka et al. [54] examined the energetic and mechanical properties of pellets produced from agricultural biomass residues. They utilised various straw types, including wheat, rapeseed, and maize. The highest bulk density values were obtained for a rapeseed–wheat mixture ($523.6 \text{ kg}\cdot\text{m}^{-3}$) and for maize straw ($566.9 \text{ kg}\cdot\text{m}^{-3}$). Carrillo-Parra et al. [55] reported significantly higher bulk density values for pine sawdust pellets, reaching $670 \text{ kg}\cdot\text{m}^{-3}$.

3.5. Elemental Composition of Raw Materials

The results of the elemental composition analysis of the tested raw materials are presented in Table 5.

Table 5. Elemental composition of the tested raw materials.

Raw Material	C $\pm$ SD [%]	H $\pm$ SD [%]	N $\pm$ SD [%]	S $\pm$ SD [%]	Cl [%]
Pine sawdust	41.84 ± 0.44	6.65 ± 0.01	0.134 ± 0.001	0.023 ± 0.001	0.004
Plum stones	54.14 ± 0.32	6.42 ± 0.02	0.72 ± 0.002	0.103 ± 0.001	0.002

The conducted analyses (Table 5) showed that the sawdust contained 41.84% carbon, whereas the crushed plum stones exhibited a slightly higher content of 54.14%. The carbon content in pine sawdust depends on multiple factors, including tree age and origin. According to the literature data, the carbon content in pine sawdust typically ranges from 45% to 55% [56,57]. In studies carried out by García et al. [58], the carbon content of pine sawdust was considerably higher at 50.6%. Similar results were reported by Lei et al. [59], who obtained a carbon content of 51.69% in pine sawdust.

The carbon content in plum stones can vary depending on the fruit variety. Voca et al. [60] reported carbon contents ranging between 52.11% and 55.29%, while Yessenbek et al. [61] obtained a comparable value of 50.54%.

The hydrogen content in both investigated raw materials was at a comparable level. Pine sawdust contained 6.65% hydrogen, while plum stones showed a slightly lower hydrogen content of 6.42%. The literature data indicate that the hydrogen content

in fruit stones (cherry, apricot, plum, peach) ranges between 5.99% and 6.70% [62,63]. Xu et al. [64] reported a somewhat lower hydrogen content in pine sawdust at 5.75%, whereas Jado et al. [65] obtained significantly higher values, with pine sawdust containing 8.13% hydrogen.

Regarding nitrogen, pine sawdust was characterised by a nitrogen content of 0.134%, while crushed plum stones contained slightly more nitrogen at a value of 0.72%. As reported by Piskowska-Wasiak [66], nitrogen present in biomass originates mainly from compounds such as proteins, nucleic acids, alkaloids, chlorophyll, and porphyrins. Its occurrence is considered disadvantageous in thermal processes due to the generation of nitrogen oxides. Standards for wood pellets require a nitrogen content below 0.3%. The EN Plus A2 certification [67] specifies a maximum nitrogen level of 0.5%, while EN Plus B sets the limit at 1%. Consequently, pellets with up to 20% plum stone addition meet the requirements of the EN Plus B certification (according to PN-EN 14961-2:2011) [67].

The analysed raw materials exhibited low sulphur contents of 0.023% for pine sawdust and 0.103% for plum stones. Obernberger [68] reported that exceeding 0.2% sulphur by weight in biomass can lead to high SO_x emissions. The presence of sulphur in fuels may also have a certain positive effect, namely the reduction in chloride-induced corrosion due to the substitution of chloride ions in sodium or potassium chlorides with sulphate ions, which form more stable compounds [69]. Hardy et al. [70] indicated that the risk of chloride-induced corrosion does not occur if the sulphur content in biomass does not exceed 0.02%.

A comparable sulphur content of 0.038% in pine sawdust was reported by Pereira et al. [71]. Pine sawdust is characterised by a much lower sulphur content compared to poplar sawdust, as Kanwal et al. [72] found sulphur contents as high as 0.38% in poplar. Similarly low sulphur values were observed in plum stones analysed by Voca et al. [60], where the average sulphur content was 0.04%.

3.6. Heat of Combustion and Heating Value of Sawdust, Crushed Plum Stones, and Rosin

Table 6 presents the results of the investigations into the heating value and heat of combustion of the raw materials used in the experiments, as well as of the produced pellets.

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}]			
Pine sawdust	19.980 ± 0.32	23.117 ± 0.32	18.231 ± 0.32	21.476 ± 0.32
Plum stones	20.485 ± 0.29	23.836 ± 0.29	18.741 ± 0.29	22.206 ± 0.29
Rosin	40.995 ± 0.41	41.131 ± 0.41	39.830 ± 0.41	39.970 ± 0.41
Pellets with 10% plum stones and 10% rosin	21.199 ± 0.38	24.954 ± 0.38	19.481 ± 0.38	23.361 ± 0.38
Pellets with 15% plum stones and 10% rosin	21.230 ± 0.41	24.993 ± 0.41	19.512 ± 0.41	23.398 ± 0.41
Pellets with 20% plum stones and 10% rosin	21.261 ± 0.30	25.026 ± 0.30	19.544 ± 0.30	23.434 ± 0.30

The results presented in Table 6 reveal clear differences in both HHV and LHV between the tested raw materials and the produced pellets. Among the analysed feedstocks, rosin exhibited significantly superior energy properties, with an average heat of combustion of HHV_{ar} = 40.995 MJ·kg^{−1} and HHV_{dry} = 41.131 MJ·kg^{−1}. This value is almost twice as high as that obtained for pine sawdust (HHV_{ar} = 19.980 MJ·kg^{−1}) and plum stones (HHV_{ar} = 20.485 MJ·kg^{−1}), underlining the high energy potential of rosin.

The combustion heat and heating values obtained for pine sawdust are consistent with the literature data [73,74]. Similar results were reported by Sermyagin et al. [75], who analysed spruce sawdust with HHV = 19.93 MJ·kg^{−1} and LHV = 17.22 MJ·kg^{−1}. Comparable findings were presented by Čajová Kantová et al. [76], who studied the

influence of spruce bark and cone additions on the quality and energy value of spruce sawdust pellets. Their results demonstrated only a minor effect of these additives on pellet quality, with LHV ranging from 17.05 to 17.5 MJ·kg⁻¹ and HHV between 18.33 and 18.69 MJ·kg⁻¹, depending on the mixture composition.

All pellets produced from mixtures of pine sawdust, plum stones, and rosin exhibited heating values exceeding 19 MJ·kg⁻¹. Consequently, they meet the requirements specified for wood pellets by ISO 17225-1:2021-11 [39], which sets the minimum heating value at 16.5 MJ·kg⁻¹.

3.7. Emission Analysis of Combustion Gases from Pellets with Plum Stone Additives

Table 7 presents the results of flue gas composition obtained during the combustion of pellets made of pine sawdust as well as mixtures containing crushed plum stones (10%, 15%, 20%) and pellets with an additional 10% of crushed rosin.

Table 7. Flue gas composition during combustion of pellets made from pine sawdust with additions of crushed plum stones and crushed rosin (10%).

Flue Composition at 10% O ₂	Plum Stones Content [%]					Ecodesign Limit Value (at 10% O ₂) [77]
	0	10	15	20	100	
CO ₂ [%]	8.68	7.16	7.03	7.02	8.37	-
CO [mg·Nm ⁻³]	337.21	633.76	603.79	572.89	1259.17	500
NO _x [mg·Nm ⁻³]	172.80	127.76	123.77	123.44	265.24	200
SO ₂ [mg·Nm ⁻³]	14.76	8.12	5.17	5.00	50.87	-
HCl [mg·Nm ⁻³]	3.03	1.19	0.39	0.32	10.62	-
Excess air coefficient λ	2.43	2.59	2.52	2.49	3.04	-
Flue gas temperature in the boiler flue [°C]	153	150	157	160	160	-

The analysis of combustion effects (Table 7) demonstrated that increasing the content of crushed plum stones in the pellet mixture (from 10% to 20%) led to a gradual rise in the flue gas temperature in the boiler outlet from 150 °C (10% addition) and further to 160 °C (20% addition). The increase in flue gas temperature under constant operating conditions of the boiler installation indicates a higher calorific content of the fuel. Thus, plum stones represent an additive that enhances the combustion heat of the produced pellets.

The CO emissions from pellets containing plum stones and 10% rosin in a Class 5 retort boiler slightly exceeded the Ecodesign Directive [77] limit of 500 mg·Nm⁻³. Specifically, CO concentrations decreased from 633.76 mg·Nm⁻³ for 10% plum stone addition to 572.89 mg·Nm⁻³ at 20%, but remained above the regulatory threshold. This exceedance is likely related to the relatively high proportion of rosin, which increases the volatile content of the fuel and can lead to incomplete oxidation under fixed boiler settings. Elevated excess air coefficients (λ = 2.43–2.59) may also indicate suboptimal air–fuel mixing during the devolatilisation phase.

To achieve full compliance with the Ecodesign limit, two measures can be considered. First, reducing the rosin content to approximately 5% would likely lower CO emissions by limiting the volatile fraction and improving burnout. Second, fine-tuning of boiler operating parameters (e.g., air distribution, feed rate, or staged combustion) could further optimise the oxidation environment, especially during the ignition and primary burn phases. Such adjustments are expected to bring CO concentrations below the required 500 mg·Nm⁻³ without compromising thermal performance. In the analysed biomass combustion conditions, the primary source of NO_x emissions is the fuel-bound nitrogen, since the combustion temperatures remain below 1300 °C. Therefore, the Zeldovich thermal mechanism is not activated, nor is the prompt-NO mechanism, due to the relatively high excess air ratio (λ).

The excess air coefficient (λ) ranged between 2.43 and 2.59 for pellets and 3.04 for unprocessed plum stones. The literature indicates typical λ values of 2.0–2.5 [78]. The observed decrease in λ with increasing plum stone content suggests more efficient contact between combustible particles and the oxidising medium.

The CO emissions from pellets containing plum stones and 10% rosin in a Class 5 retort boiler slightly exceeded the Ecodesign Directive [77] limit, which has been in force since 1 January 2020. The results showed that increasing the plum stone content from 10% to 20% reduced CO emissions from 633.76 mg·Nm⁻³ to 572.89 mg·Nm⁻³. The elevated CO values may be attributed to the high proportion of rosin, which should be reduced to approximately 5% in future formulations. Optimisation of boiler operating conditions (air–fuel ratio, mass feed rate) could further decrease CO emissions.

The NO emissions for all tested pellets met the Ecodesign [77] requirements.

Regarding chlorine emissions, most of the chlorine present in biomass is released as hydrogen chloride (HCl), which can react further in the flue gas stream, potentially forming dioxins. Upon flue gas cooling, HCl may condense as salts on heat exchanger surfaces, leading to high-temperature chloride corrosion. Although Ecodesign [77] does not specify HCl emission limits for small-scale boilers, some German standards set an acceptable threshold of <5 mg·m⁻³. In the present study, HCl emissions were consistently low, confirming the low chlorine content in the raw materials. Moreover, increasing the plum stone content in pellets further reduced HCl emissions.

Sulphur oxide (SO_x) emissions were determined primarily by the sulphur content of the fuels. During combustion, sulphur is oxidised mainly to SO₂, with minor contributions from SO₃, and forms alkali sulphates. The role of sulphur is significant not only due to SO_x emissions, but also because of its influence on corrosion mechanisms [79]. Certified wood pellets combusted in the same boiler generated SO₂ emissions of approximately 23 mg·m⁻³, which were considerably higher than those obtained for the investigated pellets.

The observed increase in flue gas temperature from 153 °C to 160 °C with higher plum stones content can be attributed to the higher calorific value and lower moisture content of plum stones compared to pure pine sawdust. Fuels with higher energy density and lower water content typically exhibit more intense combustion and higher flame temperatures, particularly under constant air supply conditions. As a result, the flue gas temperature at the boiler outlet rises with the increasing proportion of plum stones in the pellet mixture. Similar trends have been reported for biomass blends with higher calorific values, where increased energy content led to elevated flue gas temperatures under unchanged boiler settings [80].

For comparison, combustion tests of unprocessed plum stones in the same installation showed significantly poorer combustion performance and higher emission levels compared to pellets (Table 7).

4. Conclusions

Based on the conducted research on the effects of crushed plum stones and rosin on the pelletisation process and energy parameters of the produced pellets, the following conclusions were drawn:

1. Pine sawdust is characterised by an average moisture content of 13.52% and a significant fraction of fine particles (<0.5 mm), accounting for ~13% of the mass. This fraction is unfavourable for pelletisation efficiency and process safety.
2. The addition of crushed plum stones and 10% rosin enables partial compaction of the fine fraction without pressure, reducing the energy demand of the pelletisation process.

3. Incorporating 10–20% crushed plum stones into the sawdust mixture with 10% rosin (moisture ~16%) significantly decreased the pelletiser power demand—by ~18% and 25%, respectively—compared to pelletisation of pure pine sawdust.
4. The addition of crushed plum stones improved the energy parameters of pellets. The heating value increased up to $18.016 \text{ MJ} \cdot \text{kg}^{-1}$, and the heat of combustion reached $20.042 \text{ MJ} \cdot \text{kg}^{-1}$ at 20% plum stone content. An additional 10% rosin raised these values by $\sim 1.67 \text{ MJ} \cdot \text{kg}^{-1}$, an increase of 8.4%.
5. Although plum stone addition slightly reduced pellet density and bulk density, at 10% addition, the kinetic durability improved to 97.24%, indicating enhanced mechanical properties of the final product.
6. Pellets made from sawdust, plum stones, and rosin showed favourable combustion characteristics, including lower excess air coefficients (λ) and reduced emissions of CO, NO, and SO₂. However, the relatively high rosin content (10%) caused a slight exceedance of CO emission limits according to the Ecodesign Directive. A reduction in rosin content to ~5% is therefore recommended.

These results highlight the innovative potential of combining plum stones and rosin as complementary additives for pellet production, offering both improved fuel properties and opportunities for industrial application within the circular bioeconomy framework.

In summary, the results confirm the feasibility and effectiveness of incorporating crushed plum stones and rosin as modifiers in pellet production from pine sawdust. The proposed approach supports circular economy principles by enabling the valorisation of agricultural by-products and enhancing the performance of solid biofuels.

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