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Research article

Mechanical and combustion properties of sawdust—Straw pellets blended in different proportions☆

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ABSTRACT

The objective of this project was to determine the mechanical and combustion properties of pellets made of pine sawdust mixed with wheat and rapeseed straws. We determined the characteristics and quality of the pine sawdust, wheat straw and rapeseed straw agglomerates blended in different proportions, including the poured density, tapped density and the Carr compressibility index, according to standard test method ASTM D6393: 1999. To determine pellet durability, we used the Ligno tester ONORM M 7135: 2000 to perform single-pellet drop tests. We determined the strength of the pellets by diametric compression between flat plates, and measured the heat of combustion and ash content following the international standards ISO 9831: 2005 and ISO 18122: 2016, respectively. Our results reveal that the mechanical and combustion parameters are proportion-dependent. Pellet density decreased with an increased percentage of the two straw types in the mixture. An increase in compaction pressure resulted in an increase in pellet density. The mean values of the drop resistance decreased with the addition of wheat starch, and this decrease was lower for mixtures with a higher moisture content and compaction pressure. Mixtures of sawdust with ground rapeseed straw yielded pellets of higher durability and drop resistance. The swirled durability of mixtures with rapeseed straw was not dependent on the percentage contributions of rapeseed straw and moisture content. Pellet strength decreased with the addition of ground straw. We observed a decrease in strength with an increase in moisture content and an increase in strength with increasing compaction pressure. In addition, we observed a decrease in the heat of combustion with an increase in the percentage contribution of straw in the mixture.

1. Introduction

The by-products and wastes of agricultural and wood industries are a major source of the biomass used in the production of biofuels and biomaterials. There is a growing need for the development of biodegradable materials and the compaction of ground biomass to allow for easier and more predictable handling and processing [1,3,7,9,17,22,24,25]. Pelletization provides good material feeding with little dust formation [8]. In recent years, the importation of pellets from outside Europe has increased [16]. The transport of biofuel pellets is economically profitable and environmentally sustainable, even if milling is required prior to combustion in pulverized systems [16]. The majority of pellets on the world market is produced from sawdust; however, the intense market demand for biomass pellets has generated growing interest in the search for new resources that might be suitable as additives in the pelletization process [6].

Biomass materials are frequently mixed to obtain and improve the properties and quality of pellets [21]. The quality of pellets is related to their physical, chemical and mechanical properties. Certain European countries have developed standards specifying control parameters and guidelines for the biomass products on the market. Garcia-Maraver et al. [7] and Serrano et al. [24] conducted comparative analyses of established standards and recommendations. These standards include parameters and guidelines regarding particle and bulk density, moisture content, durability, particle size, chemical composition, ash content and heating value. The authors called for the establishment of international standards to facilitate the purchase and sale of biomass fuels on the global market. Temmerman et al. [29] reviewed the methods used in different laboratories to determine durability, and which adhere to various standards. The authors concluded that, in addition to the biofuel itself, durability values were influenced by the durability determination method applied. They found no relationship between durability and particle density. Garcia-Maraver et al. [7], Serrano et al. [24], and Temmerman et al. [29] listed the existing standards for determining the parameters of biomass in both briquette and pellet form. International standard ISO 17831-2 [12] defines the method for determining the mechanical durability of briquettes. The parameters examined in

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this study are among the most important standards for the characterization of pellets. ISO 17225 [13] lists the quality classes and specifications for solid biofuels originating from forestry, agriculture and aquaculture. Numerous studies have been recently published regarding the properties of pellets and briquettes. Kaliyan and Morey [17] conducted a broad review of factors affecting the strength and durability of densified biomass products, and made recommendations regarding the selection of process parameters in the production of agglomerates of acceptable quality and durability. The authors presented guidelines for the development of standards and criteria regarding acceptable levels of strength and durability of these densified products. Liu et al. [21] examined rice straw pellets and pellets of mixed rice straw and bamboo at different mixing ratios. The bamboo and rice straw pellets with particles <2 mm in size were uniformly mixed at different weight ratios. The authors concluded that all the pellets they examined met the physical properties and quality levels required by existing standards, except for a material pellet density with a mixing ratio ≤3:2 of bamboo and rice straw, respectively. The authors also showed that mixing different kinds of biomass might be an effective way to optimize the properties of biomass solid fuel. The addition of bamboo to rice straw resulted in a decrease in the degree of inorganic ash from 16% to 2%, and a higher gross calorific value. In Lu et al.'s [22] study of the effects of adding binders to wheat straw pellets, the authors compressed wheat straw with crude glycerol, bentonite, lignosulfonate, wood residue and pre-treated wood residue with crude glycerol into a single pelleting unit at a temperature of 95 °C. The authors concluded that the addition of binders increased the tensile strength from 1.13 MPa to 1.63 MPa. Increases were observed in the heating value by the addition of crude glycerol, wood residue and pre-treated wood residue as binders. Kaliyan and Morey [17] investigated the effect of pressure, moisture content, particle size and preheating temperature on the densification characteristics of corn stover and switchgrass. Similar examinations were performed by Ishii and Furuichi [11] on rice straw agglomerates. The authors determined the optimum moisture content range for producing rice straw pellets with a high yield ratio and high heating value. They also determined the influence of particle size and forming temperature on the yield ratio and durability of rice straw pellets. At forming temperatures of 60 °C or 80 °C, the optimum moisture was proposed as being between 13% and 20%. Shaw et al. [25] investigated steam explosion pre-treatment, die temperature, particle size and moisture content on the physical quality of pellets produced from poplar wood and wheat straw. The authors concluded that pre-treated materials yielded higher density and tensile strength than untreated materials, and that an elevation in temperature and decrease in particle diameter resulted in a higher physical quality of pellets. Adapa et al. [1] investigated the density and specific energy required for compacting barley, canola, oat and wheat straw at a 10% moisture content. They found that the minimum specific energy consumption to produce the highest density of pellets occurred at a pressure of approximately 63 MPa for barley and wheat, and at approximately 94 MPa for canola and oat.

Particle size distribution plays an important role in the production of pellets. Bergstrom et al. [3] studied the influence of raw material particle size distribution on the process and the physical and thermomechanical characteristics of produced fuel pellets. The study results indicated that particle size distribution had some effect on current consumption and compression strength, but no effect on single-pellet or bulk density, moisture content, or moisture absorption during storage and abrasion. The authors suggested the need to grind sawdust particle sizes to below 8 mm. Lee et al. [20] examined the influence of species, wood particle size, moisture content, pelletizing temperature and time on the durability of larch and tulipwood pellets. The authors noted differences in the durability of pellets produced from the two materials and found that the durability of larch pellets was significantly higher than that of tulipwood pellets. In addition, larch pellets comprising smaller particles were more durable, and the durability improved steadily with increasing pelletization time and temperature. Ground straw is widely used in the production of biomass pellets, and the effects of moisture content, particle size and the addition of pine on the quality parameters of barley straw pellets were investigated by Serrano et al. [24]. The authors evaluated the durability, density, length and moisture of pure straw and blended pellets, and also determined the heating value and ash content. They found that the optimum moisture content for dense barley straw pellets ranged from 19% to 23%. Durability was found to reach 95.5%, and even increased up to 97–98%, with the addition of a small amount of pine sawdust. The agglomeration of ground material was improved by the addition of water and pine sawdust, while coarser grinding showed no negative effect on barley straw pellets. An analysis of the effect of biomass composition and milling size on pelletization parameters was performed by Castellano et al. [6]. Materials were milled to pass through a 2-mm and 4-mm screen mesh, and the authors analysed the mechanical durability and fines content of the pellets, as well as power demand. Their results showed that pellets made from 2-mm particles showed higher mechanical durability, and pellets made of woody materials showed better physical qualities. Gilbert et al. [8] conducted a study on the pressure pelletization of switchgrass for five types of material preparation: raw, raw shredded, torrified and switchgrass combined with heavy pyrolysis oil and wheat straw. They examined the influence of compaction pressure and temperature on the quality of pellets in terms of their density, mechanical strength and durability.

The growing market demand for renewable fuels has stimulated the search for new biomass types suitable for pelletizing [6]. To reduce transportation costs, careful management is required of the agricultural, wood and aquaculture residues from nearby areas [11]. A literature review also points to the need to identify new kinds of fuels by mixing well-known materials, and the characteristics of these materials must be established. There is no information in the existing literature regarding the properties of mixtures of sawdust and cereal straws, and there is scant information about the characteristics of rapeseed straw compaction in pellet production. The objective of our project was to determine the mechanical and combustion properties of pellets produced of pine sawdust mixed with wheat or rapeseed straw. Lublin Voivodship is a major producer of rapeseed and wheat in Poland, and research is needed on the optimization of production of renewable fuels from locally available biomass. We examined the quality of agglomerates produced without any binders or additives. The pellets used in our tests were produced in a single-die pelletizer [1,17,22,25], a laboratory-scale pelletizer with higher capacities and a semi-industrial-scale pelletizer [3,6,11,21,24]. We used a single unheated die in the project presented below.

2. Materials and methods

For our experimental materials, we chose three types of granular biomass easily accessible from the Lubelskie Voivodship: pine sawdust, wheat straw and rapeseed straw. We obtained pine sawdust, a by-product of furniture manufacturing, from a local furniture factory, and the wheat and rapeseed straws were donated by the Warsaw University of Life Sciences. After delivery, materials were dried in a thin layer under laboratory conditions. We cut the wheat and rapeseed straw into 20-mm long particles, then milled them in a hammer mill with 1-mm screen size. Next, we prepared blends of the sawdust with the two kinds of straw. The proportions of ingredients in the mixtures are shown in Table 1.

We blended weighted amounts of ingredients in a laboratory mixer for 6 h. Tables 2 and 3 list the particle size distribution of the mixtures with two moisture content levels—8% and 20%, respectively. We added distilled water and mixed the materials in the laboratory mixer for 15 min every hour over a 24-hour period to obtain a 20% moisture content. The moisture content levels correspond to those currently in practice in the commercial production of pellets. Castellano et al. [6] performed experiments at moisture contents between 10% and 12%. As reported by Kaliyan and Morey [17], these moisture content levels are commonly used in pellet production. To estimate the moisture

Table 1
Proportions of ingredients in mixtures used in experiments.

Mixtures of sawdust and wheat straw		Mixtures of sawdust and rapeseed straw	
Sawdust %	Wheat straw %	Sawdust %	Rapeseed straw %
0	100	0	100
20	80	20	80
40	60	40	60
60	40	60	40
80	20	80	20
100	0	100	0

content, we weighed 200–300-g samples before and after the 24-h drying at 105 °C in a laboratory oven, and we calculated the moisture content on a "wet basis."

Next, we determined a set of parameters, termed Carr indices (CIs), using a Hosokawa Powder Tester and followed the methods recommended by ASTM D6393 [4]. We determined the poured density ρ_0 and tapped density ρ_1 of the experimental materials in a Hosokawa Micron Powder Characteristics Tester, Type PT-S [10]. The poured density ρ_0, in kg/m^3, is the bulk density of loose particulate deposits built up in a vessel by dropping, as per the injection method. The packed density ρ_1, in kg/m^3, is the bulk density of tapped loose material. We obtained the tapped density by tapping the sample 180 times.

To describe material flowability, we used a PT-S Tester to determine the Carr compressibility index CI(%) [5] of the materials, which we calculated as follows: $CI(\%) = 100 \times (\rho_1 - \rho_0) / \rho_1$. Higher compressibility is associated with lower flowability. In industrial practice, it is assumed that powder has good flowability when the CI is in the range from 5% to 15%. The CI results are presented in Table 4. Using the same tester, another widely used parameter, the Housner ratio, defined as $R_h = \rho_1/\rho_0$, may be also calculated. In industrial practice, it is considered that durable tablets may be produced from powder having an Rh no higher than 1.6. We performed sieve analysis on a vibrating stack of sieves with the following mesh sizes: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.9, 1.0, 1.6 and 2.0 mm.

We compacted the materials into a cylindrical die 10 mm in diameter and 25 mm high. Fig. 1 shows the arrangement of the experimental pelletizer. We placed the cylindrical die on a steel table and filled it with loose material. The sample filled the entire volume of the cylinder. After filling, we placed a piston on the material surface and conducted compaction using a high-pressure actuator and yoke. In the experiments, we applied compaction pressures of 60 MPa and 120 MPa. We measured the compaction pressure with the load cell mounted between the piston and the yoke. We removed the compacted pellets from the cylinder using the same piston after replacing the base with one having a hole 1 mm larger than the cylinder diameter.

We determined the durability of the produced pellets using a Ligno Tester, as recommended by ONORM M 7135 [29], by measuring the drop resistance on a concrete flat surface from a 1-m height. The Ligno Tester we used was produced according to the Austrian standard ONORM M 7135 [23], which refers to the commercial device Ligno-Tester LT II of Borregaard Lignotech. We swirled the pellet sample using the defined air stream, and the particles collided against each other and against the perforated walls of the test chamber according to the defined geometry and dimensions. The chamber is a four-sided pyramid oriented with its tip downward, with walls perforated by 2-mm-diameter round holes. We placed 100 g of tested pellets in the test chamber and set the air stream through the chamber to 70 mbar for 60 s. The durability is expressed as the percentage of the mass of pellets remaining in the chamber compared to the initial sample mass [29]. We then conducted a drop test, consisting of the free fall of a single pellet from a height of 1 m to a concrete surface. We tested ten pellets approximately 10-mm in length for each variant of the experiment, and measured the mass of each pellet prior to and after the drops, and the weight loss percentage as a measure of durability.

We tested the strength of the pellets by diametric compression between a circular plate and stamp, as commonly applied in tests of pharmaceutical tablets (e.g., [26]). The stamp moved down at a constant deformation rate of 0.033 mm/s, and we recorded the real time, compression force in N and displacement in mm of the moving stamp. We measured the maximum compression force at breaking point B and calculated the breaking strength of the agglomerates σ_B according to Fell & Newton [30]: $\sigma_B = \frac{2F_B}{\pi dh}$, where: F_B is the breaking force, d is the tablet diameter and h is the height of the tablet. Tests were repeated ten times.

We determined the heat of combustion (HC) using the calorimetric method recommended by ISO 9831 [15], using a semiautomatic AC 600 LECO device [19]. We burned 1-g tablets of the tested material in a calorimetric bomb in oxygen atmosphere at 3 MPa, and initiated combustion with a Kanthal resistance wire. We measured the HC using the TrueSpeed method, which was calculated automatically with AcWin software. The HC process yielded a lower heating value when subtracting the heat of vaporization. We determined the ash content using ISO 18122 [14], and performed all measurements three times.

We performed an analysis of variance on the obtained data using the STATISTICA 12 package [28]. The statistical significance of the data is given as 0.95 confidence intervals shown as bars on a graph, where p is the calculated probability (or level of statistical significance) and the F is the Snedecor test function. The higher the F value, the stronger the effect of a given factor on the determined parameter.

3. Results

Tables 2 and 3 show the results of the sieve analysis of the experimental materials. In the case of pure pine sawdust, we obtained the highest percentages for the fraction 0.2 < d < 0.1 of 21.6% and 22.2% for 8% and 20% moisture contents (m.c.), respectively, and the lowest

Table 2
Sieve analysis of sawdust and its mixture with wheat straw for two values of moisture content.

Percentage of sawdust [%]	Percentage of wheat straw [%]	Moisture content [%]	Sieve analysis										
			d > 2.0	2.0 < d < 1.6	1.6 < d < 1.0	1.0 < d < 0.9	0.9 < d < 0.6	0.6 < d < 0.5	0.5 < d < 0.4	0.4 < d < 0.3	0.3 < d < 0.2	0.2 < d < 0.1	0.1 < d < bottom
0	100	8	9.5	0.5	0.5	57.4	5.2	5.3	3.8	5.4	3.8	6.0	2.8
20	80	8	1.7	1.1	0.4	50.2	5.9	7.7	4.3	8.3	5.5	10.4	4.6
40	60	8	2.6	1.5	0.5	45.3	8.7	6.2	5.0	7.8	6.3	10.7	5.5
60	40	8	4.6	1.8	0.5	30.2	9.5	6.9	5.3	9.1	8.1	16.3	8.0
80	20	8	6.3	2.3	0.5	22.0	9.9	7.5	4.9	11.2	10.1	17.9	8.0
100	0	8	3.9	2.1	0.4	12.6	9.8	6.4	6.5	13.8	14.0	21.6	8.7
0	100	20	1.4	4.1	0.4	61.0	7.4	4.4	5.9	6.2	3.6	5.3	1.1
20	80	20	2.2	2.0	0.4	57.7	8.0	5.9	3.9	7.1	5.4	6.6	1.1
40	60	20	3.4	5.8	0.3	42.9	9.5	6.9	5.1	8.8	7.6	8.7	1.6
60	40	20	5.4	6.4	0.5	29.9	9.6	7.8	3.6	10.6	9.5	13.7	3.3
80	20	20	7.2	4.2	0.6	24.7	10.1	8.3	3.6	12.5	9.9	16.0	2.9
100	0	20	7.9	3.8	0.5	14.7	7.5	6.4	3.4	17.0	9.6	22.2	7.4

Table 3
Sieve analysis of sawdust and its mixture with rapeseed straw for two values of moisture content.

Percentage of sawdust [%]	Percentage of rapeseed straw [%]	Moisture content [%]	Sieve analysis d > 2.0	2.0 < d < 1.6	1.6 < d < 1.0	1.0 < d < 0.9	0.9 < d < 0.6	0.6 < d < 0.5	0.5 < d < 0.4	0.4 < d < 0.3	0.3 < d < 0.2	0.2 < d < 0.1	0.1 < d < bottom
0	100	8	0.8	1.2	0.6	51.7	10.8	5.6	5.3	5.7	5.4	9.6	3.6
20	80	8	1.5	1.2	0.6	47.7	11.3	5.6	5.0	6.9	5.8	10.3	4.3
40	60	8	3.1	1.9	0.5	40.0	11.1	6.3	5.1	8.2	6.8	12.1	4.8
60	40	8	4.4	2.0	0.4	28.6	10.8	8.1	4.4	11.1	8.5	15.9	5.8
80	20	8	4.2	2.1	0.4	21.4	10.3	8.2	4.9	12.7	10.2	18.4	7.3
100	0	8	3.9	2.1	0.4	12.6	9.8	6.4	6.5	13.8	14.0	21.6	8.7
0	100	20	1.4	2.9	0.4	59.4	8.9	6.4	3.5	6.3	5.4	4.9	1.1
20	80	20	2.5	6.4	0.5	52.9	8.4	6.4	3.5	6.3	5.4	6.9	1.1
40	60	20	9.3	14.5	2.1	36.0	7.5	6.2	3.6	6.1	5.5	8.3	1.4
60	40	20	10.1	9.3	0.4	28.1	9.0	7.7	3.9	9.5	8.0	12.1	2.3
80	20	20	6.1	3.1	0.5	23.6	10.7	9.2	5.1	13.4	10.6	15.9	2.4
100	0	20	7.9	3.8	0.5	14.7	7.5	6.4	3.4	17.0	9.6	22.2	7.4

values of 0.4% and 0.5% for the fraction 1.6 < d < 1.0. Moreover, the sawdust fractions 1.0 < d < 0.9, 0.4 < d < 0.3 and 0.3 < d < 0.2 were relatively high, at approximately 10% and 15%. In the cases of pure ground wheat straw and rapeseed straw, the largest share was that of the 1.0 < d < 0.9 fraction (between 50% and 60%). The largest contribution of pellets with particles larger than 2 mm (9.5%) was by wheat straw. This is probably an effect of the fibrous nature of wheat straw. For both pure straws, other fraction contents varied from 0.5% to 10%. In mixtures of sawdust with wheat and rapeseed straw, a higher m.c. resulted in a decreased percentage of the smallest fraction (below 0.1 mm). This was due to the water action resulting in more resilient web fibres. The m.c. of the ground materials influences the passage of particles through the sieve meshes.

Table 4 shows the poured densities and parameters describing flowability in a simple manner: the compressibility CI(%) and Hausner ratio Rh. The poured density of pine sawdust with an m.c. of 8% was 140 kg/m^3, while at a 20% m.c. the poured density was lower at 109 kg/m^3. For wheat straw, the poured density was 121 kg/m^3 and this was the lowest value measured. Also in this case decrease in poured density to 112 kg/m^3 content with an increase in moisture content was observed.

The poured densities of material mixtures increased with an increase in the portion of pine sawdust. For drier materials, we obtained the highest poured densities at 40% sawdust and 60% wheat straw, and for 80% sawdust and 20% rapeseed straw. At 20% m.c., we obtained the highest poured density value of 130 kg/m^3 for 80% sawdust mixed with wheat straw, and a poured density of 126 kg/m^3 for a maximum addition of 80% rapeseed straw to the sawdust. We observed a higher increase in density after tapping for mixtures with wheat starch with lower moisture contents. The tapped density for sawdust was 188 kg/m^3 for an 8% m.c. and 158 kg/m^3 for a 20% m.c. The density of pure ground wheat straw increased to 157 kg/m^3 after tapping and to 143 kg/m^3 for 8% and 20% m.c., respectively. The tapped density of rapeseed straw increased to 169 kg/m^3 and to 128 kg/m^3 for 8% and 20% m.c., respectively. The poured and tapped densities of polydisperse blends have been reported to be strongly affected by the shape and surface condition of single particles, and this effect is stronger at higher moisture contents [27]. Small changes in the tapped densities for different amount of smaller and bigger particles could be due to the forming of a relatively rigid structure of large particles with small particles moving freely and filling the voids. The Hausner ratio and compressibility (R_h < 1.25; CI = 5–15%) values indicated that mixtures containing 80%

Table 4
Poured and tapped density of granular biomass.

Percentage of sawdust [%]	Percentage of wheat straw [%]	Moisture content [%]	Poured density ρ_0 [kg$*$m^{-3}]	Tapped density ρ_1 [kg$*$m^{-3}]	Compressibility CI [%]	Hausner ratio R_h
0	100	8	121.0 ± 2.6	157.0 ± 3.0	22.9	1.29
20	80	8	134.3 ± 3.5	177.0 ± 3.5	24.1	1.31
40	60	8	141.3 ± 2.3	182.0 ± 1.0	22.4	1.28
60	40	8	134.0 ± 2.6	173.0 ± 0.1	22.5	1.29
80	20	8	136.0 ± 2.6	178.7 ± 3.2	23.9	1.31
100	0	8	140.3 ± 5.7	188.7 ± 1.2	25.6	1.34
0	100	20	112.3 ± 1.2	143.3 ± 1.5	21.6	1.27
20	80	20	117.0 ± 4.6	150.7 ± 4.0	22.3	1.29
40	60	20	127.3 ± 3.8	155.3 ± 2.5	18.0	1.22
60	40	20	122.7 ± 1.2	167.3 ± 2.1	26.7	1.36
80	20	20	130.7 ± 2.5	174.3 ± 2.1	25.0	1.34
100	0	20	109.0 ± 2.6	158.7 ± 2.3	31.3	1.45
0	100	8	144.3 ± 1.2	169.67 ± 0.6	14.9	1.17
20	80	8	150.3 ± 0.6	182.00 ± 2.0	17.4	1.21
40	60	8	139.3 ± 1.2	173.00 ± 1.0	19.5	1.24
60	40	8	149.7 ± 3.0	188.33 ± 1.2	20.5	1.25
80	20	8	152.3 ± 1.2	190.00 ± 1.0	19.8	1.24
100	0	8	140.3 ± 5.7	188.67 ± 1.2	25.6	1.34
0	100	20	108.0 ± 1.0	128.33 ± 0.6	15.8	1.18
20	80	20	126.0 ± 0.0	148.67 ± 0.6	15.2	1.18
40	60	20	123.3 ± 2.3	163.33 ± 3.0	24.5	1.32
60	40	20	118.0 ± 1.0	156.33 ± 1.5	24.5	1.32
80	20	20	113.7 ± 3.8	160.67 ± 2.1	29.3	1.41
100	0	20	109.0 ± 2.6	158.67 ± 2.3	31.3	1.45

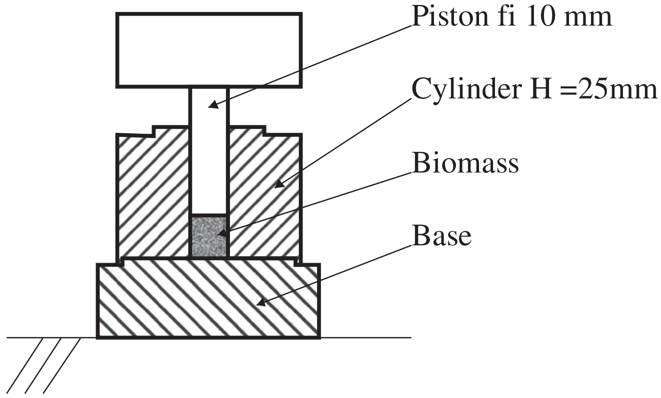

Fig. 1. Test pelletizer used for biomass compression.

or more rapeseed straw have good flowability at both tested moisture contents. Mixtures with 60% rapeseed straw at 8% m.c. and with 60% wheat straw at 20% m.c. had moderate flowability, and the flowability of all other tested materials was poor. From the pharmaceutical technology perspective, materials with an R_h value no higher than 1.6 can produce durable tablets, and in each of our tested materials this condition was fulfilled.

After their removal from the die, we measured the heights of the pellets with a manual micrometer and the results are presented in Fig. 2. Pellets made of pure sawdust were approximately 8-mm high, those made of ground straw were approximately 10 mm, and those made of wheat and rapeseed straw were 8.5 mm. After their removal from the die, the heights of pellets made of a mixture of materials increased with an increase in ground straw. The height of all pellets decreased with increased compaction pressure, due to the formation of stronger bonds between the particles. One effect of the increase in compaction pressure was increased strength in the case of rapeseed straw ($F = 40.76$) as compared to that of wheat straw ($F = 28.6$). Regarding moisture content, we observed a stronger influence on height for mixtures of sawdust and wheat straw ($F = 166.3$). We observed no moisture content effect on sawdust and rapeseed straw mixtures. This could be due to the different internal structure of stalks of wheat and rapeseed.

True density is an important factor that determines the market value of pellets. The increase in density reduces market costs of transport, handling and processing of solid biomass fuel. The calculated density results of the tested materials are presented in Fig. 3. Pellets of pure sawdust had a density of 800 kg/m^3, while the density of straw pellets equalled 650 kg/m^3 and 710 kg/m^3 for wheat and rapeseed straws, respectively. The density of the material with the highest proportion of wheat straw (60%–80%)—650 kg/m^3—was equal to that obtained for pure wheat straw.

The density of compacted mixtures of sawdust and rapeseed straw ranged from 820 kg/m^3 for a 20% addition of rapeseed straw to approximately 780 kg/m^3 with an 80% addition of rapeseed straw. We observed a weak effect of the addition of rapeseed straw on density. The density of pellets mixed with sawdust and wheat straw decreased with an increase in moisture content. This is a spring back effect after removing the compression load, which is higher in wet material. Similar behaviour was reported in the case of starches [27]. A higher moisture content resulted in a 25% decrease in density from 800 kg/m^3 to 600 kg/m^3. We observed no influence of moisture content on density in compressed mixtures of sawdust and rapeseed straw. For both kinds of mixtures, an increase in the compaction pressure resulted in an increase in pellet density. The influence of compaction pressure was stronger in mixtures with wheat straw.

Durability is a chief quality parameter in densified biomass. In our study, we performed two tests to determine durability. First, we conducted a drop test of the material to a flat surface from a 1-m height. In the second test, we swirled the material in a closed space, as per ONORM M 7135 [23], and the results are shown in Tables 5 and 6. The mean values of drop durability decreased with a growing proportion of wheat straw. We observed a maximum decrease in drop durability in dry material at 60 MPa of compaction pressure—from approximately 96% for pure sawdust to 66% for an 80% addition of wheat straw. We observed a minimum decrease in drop durability for wet material at a compaction pressure of 120 MPa. For a compaction pressure of

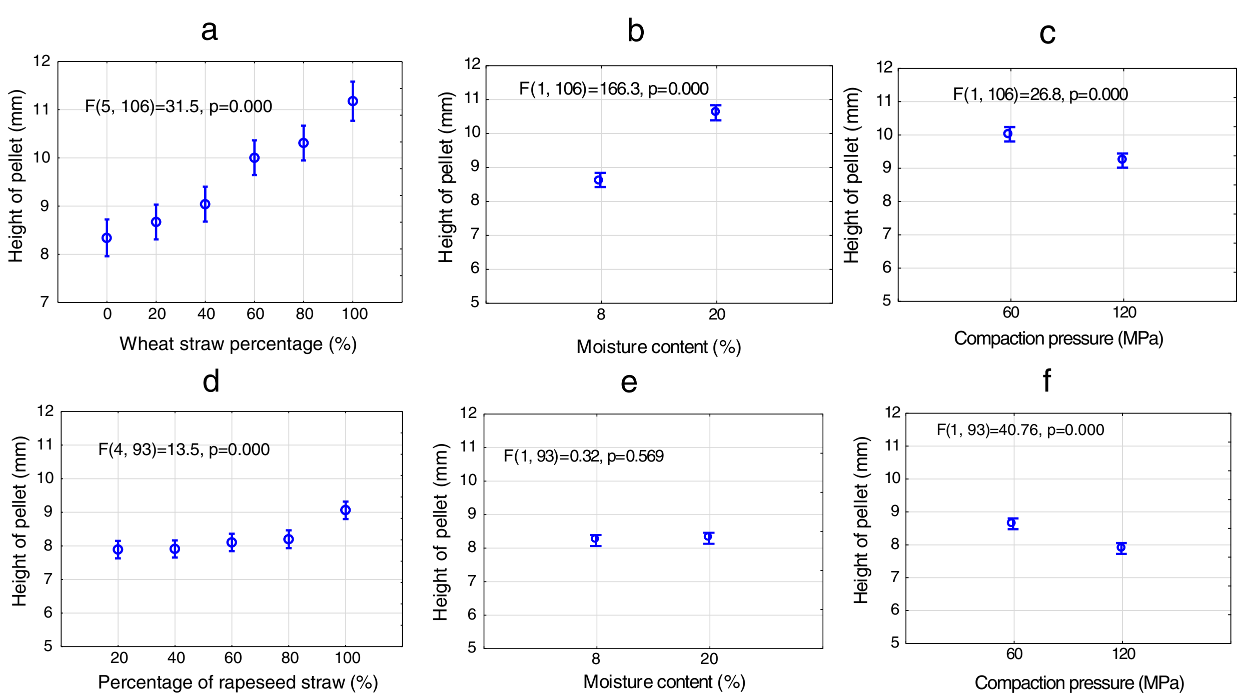

Fig. 2. Mean values of pellet height after realised from die for sawdust-wheat straw mixtures a) b) c) and sawdust-rapeseed straw mixtures d) e) f). Mean values in columns are calculated for whole range of parameters from two others. Vertical bars denote 0.95 confidence intervals; F, p - analysis of variance parameters.

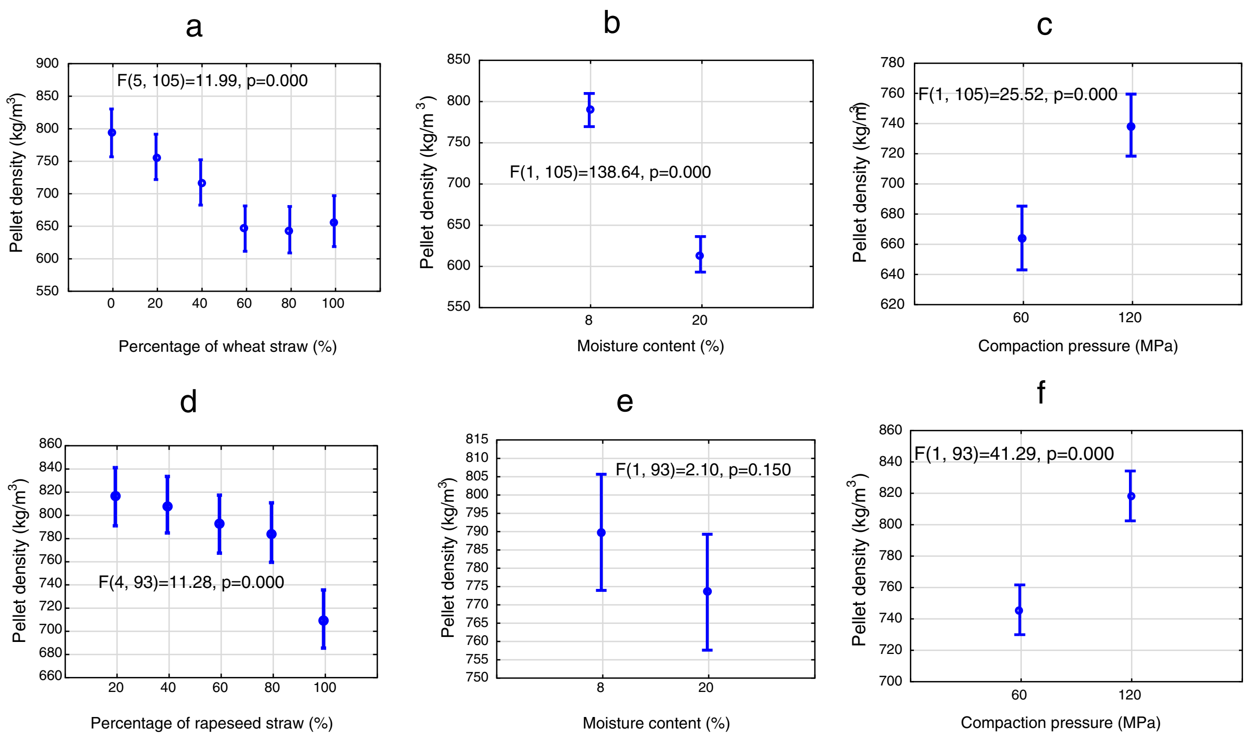

Fig. 3. Mean values of pellets density for sawdust-wheat straw mixtures a) b) c) and sawdust-rapeseed straw mixtures d) e) f). Mean values in columns are calculated for whole range of parameters from two others. Vertical bars denote 0.95 confidence intervals; F, p - analysis of variance parameters.

120 MPa, the drop resistance was stable and we observed no m.c. influence. In mixtures of sawdust and wheat straw, an increase in compaction pressure from 60 MPa to 120 MPa resulted in an increase in drop resistance of approximately 15% (see Table5).

The measured durability values from the swirling test [23] were unacceptable, ranging from approximately 60% (120-MPa compaction pressure for wet material) to approximately 20% (60-MPa compaction pressure for dry material). We observed a decrease in durability with an increase in the addition of wheat straw, while an increase in compaction pressure increased durability by 30%. We observed no m.c. effect on durability in mixtures of sawdust and wheat straw (See Table 5).

We obtained higher durability and drop resistance for pellets composed of mixtures of sawdust and rapeseed straw (See Table 6). The proportion of rapeseed straw did not significantly affect drop resistance, while we observed a higher increase in drop resistance with an increase in moisture content. In wheat straw mixtures, we obtained higher drop resistance for materials consolidated under higher compaction

Table 5
Durability sawdust - wheat straw pellets.

Percentage of sawdust [%]	Percentage of wheat straw [%]	Moisture content [%]	Compaction pressure [MPa]	Drop resistance [%]	Durability [%]
0	100	8	60	69.7 ± 8.5	20.2 ± 1.1
20	80	8	60	66.2 ± 14.7	21.4 ± 1.0
40	60	8	60	83.9 ± 8.7	26.5 ± 3.2
60	40	8	60	94.7 ± 5.7	44.9 ± 2.4
80	20	8	60	93.1 ± 5.2	55.5 ± 3.2
100	0	8	60	96.3 ± 2.9	59.5 ± 4.3
0	100	20	60	87.8 ± 5.4	34.7 ± 2.3
20	80	20	60	88.2 ± 7.9	42.8 ± 2.0
40	60	20	60	78.1 ± 16.9	49.6 ± 1.6
60	40	20	60	85.5 ± 10.4	43.3 ± 3.9
80	20	20	60	93.8 ± 5.3	48.3 ± 3.5
100	0	20	60	98.0 ± 2.0	50.4 ± 3.4
0	100	8	120	90.3 ± 6.2	42.2 ± 3.6
20	80	8	120	85.9 ± 5.1	46.1 ± 2.5
40	60	8	120	99.2 ± 1.8	58.7 ± 4.5
60	40	8	120	99.2 ± 1.1	62.7 ± 2.1
80	20	8	120	100.0 ± 0.0	75.3 ± 1.8
100	0	8	120	100.0 ± 0.0	77.8 ± 2.6
0	100	20	120	95.3 ± 2.9	55.3 ± 3.6
20	80	20	120	95.3 ± 2.8	56.5 ± 2.2
40	60	20	120	94.9 ± 6.9	53.3 ± 1.9
60	40	20	120	94.2 ± 7.5	51.6 ± 7.4
80	20	20	120	97.5 ± 1.7	60.7 ± 5.5
100	0	20	120	98.4 ± 1.6	61.2 ± 4.5

Table 6
Durability of sawdust - rapeseed straw pellets.

Percentage of sawdust [%]	Percentage of wheat straw [%]	Moisture content [%]	Compaction pressure [MPa]	Drop resistance [%]	Durability [%]
0	100	8	60	84.5 ± 4.6	40.65 ± 1.9
20	80	8	60	91.3 ± 4.8	32.53 ± 6.3
40	60	8	60	97.1 ± 5.5	49.91 ± 3.8
60	40	8	60	99.2 ± 1.1	47.94 ± 1.8
80	20	8	60	99.7 ± 5.7	58.75 ± 2.0
100	0	8	60	96.3 ± 2.9	59.54 ± 4.3
0	100	20	60	100.0 ± 0.0	47.29 ± 3.7
20	80	20	60	97.9 ± 2.1	42.88 ± 3.9
40	60	20	60	99.2 ± 1.2	54.12 ± 6.3
60	40	20	60	99.6 ± 0.9	50.41 ± 2.3
80	20	20	60	97.2 ± 4.2	42.93 ± 3.9
100	0	20	60	98.0 ± 2.0	50.36 ± 3.3
0	100	8	120	100.0 ± 0.0	51.89 ± 3.1
20	80	8	120	100.0 ± 0.0	47.65 ± 2.1
40	60	8	120	99.6 ± 0.9	48.27 ± 3.1
60	40	8	120	100.0 ± 0.0	47.85 ± 6.1
80	20	8	120	100.0 ± 0.0	75.39 ± 3.6
100	0	8	120	100.0 ± 0.0	77.79 ± 2.6
0	100	20	120	99.6 ± 0.9	54.8 ± 2.9
20	80	20	120	95.5 ± 6.8	46.8 ± 3.9
40	60	20	120	97.2 ± 4.2	61.5 ± 3.7
60	40	20	120	98.4 ± 1.7	56.6 ± 2.1
80	20	20	120	98.3 ± 1.8	41.8 ± 4.4
100	0	20	120	98.4 ± 1.6	61.2 ± 4.5

pressure. The percentage of mass after drop was high and ranged between 98% and 100%. We found the swirled durability of mixtures with rapeseed straw to be independent of the proportion of straw. For different m.c. values, we obtained similar results. We observed increases in durability of between 15% and 20% only for higher compaction pressure.

The mechanical strength σ_B of the produced pellets are shown in Fig. 4. The strength of pure sawdust pellets was 0.5 MPa, whereas the strength of pure wheat straw was 0.25 MPa. We observed a significant decrease in strength with an increase in the proportion of wheat straw. With an 80% addition of wheat straw, the pellet strength decreased to 0.2 MPa. The strength of pellets was also lower at higher moisture contents. We observed a strong increase in the mean strength values of the pellets at higher compression pressures.

Pellets made of mixtures of sawdust and rapeseed straw were stronger (see Fig. 4a), with mean strength values about 10–15% higher than

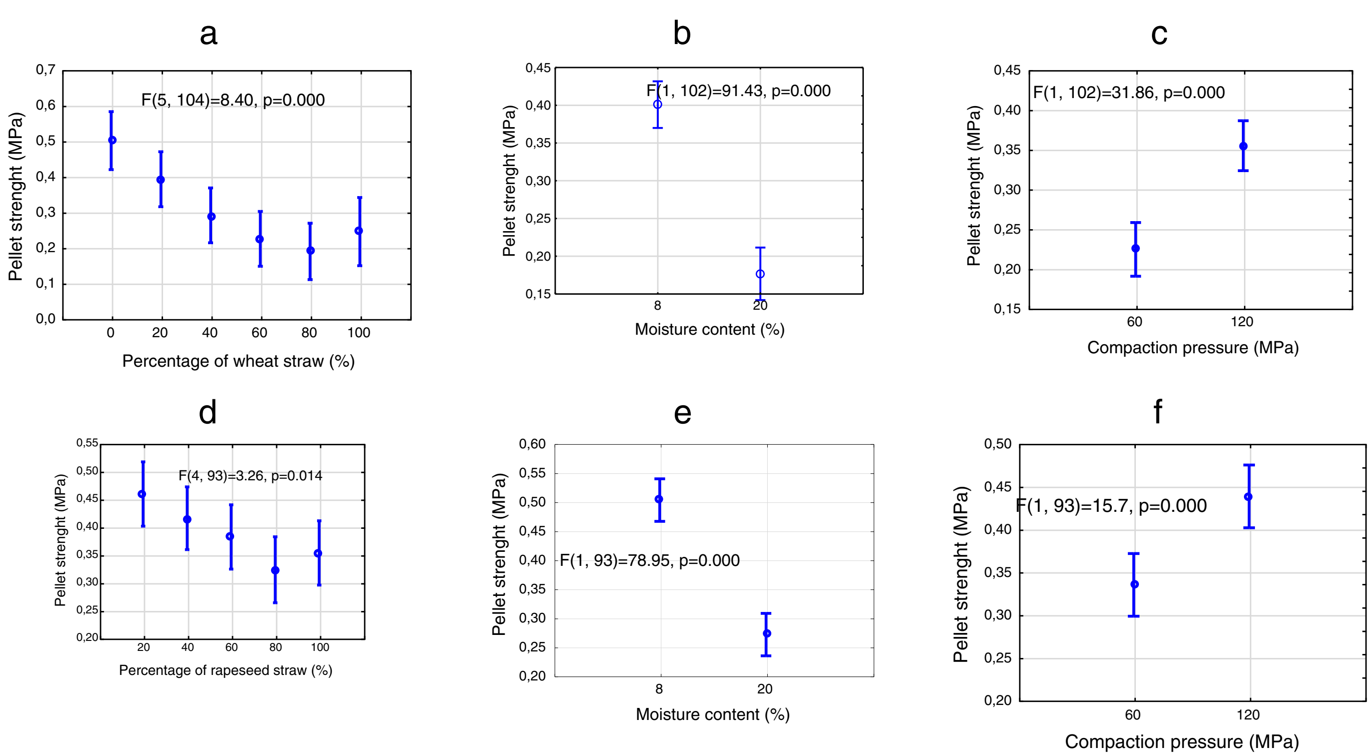

Fig. 4. Mean values of strength of the pellets σ_B as dependent on proportion of straw, moisture content and compaction pressure for sawdust-wheat straw mixtures a) b) c) and sawdust-rapeseed straw mixtures d) e) f). Mean values in columns are calculated for whole range of parameters from two others. Vertical bars denote 0.95 confidence intervals; F, p - analysis of variance parameters.

Table 7
Heat of combustion HC, of tested mixtures of biomass.

Percentage of sawdust [%]	Percentage of wheat straw [%]	Moisture content [%]	Heat of combustion (LHV)[MJ/kg]	Ash content in dry mass [%]
0	100	8	17.5 ± 0.5	4.10
20	80	8	17.6 ± 0.2	3.58
40	60	8	17.9 ± 0.2	2.96
60	40	8	18.1 ± 0.1	2.19
80	20	8	18.3 ± 0.2	1.24
100	0	8	18.5 ± 0.1	0.31
0	100	20	15.2 ± 0.2	
20	80	20	15.4 ± 0.1	
40	60	20	15.5 ± 0.1	
60	40	20	15.8 ± 0.2	
80	20	20	16.2 ± 0.2	
100	0	20	16.8 ± 0.2	
0	100	8	16.5 ± 0.2	7.92
20	80	8	16.9 ± 0.1	6.16
40	60	8	17.4 ± 0.1	5.26
60	40	8	17.8 ± 0.2	4.82
80	20	8	18.1 ± 0.1	2.91
100	0	8	18.5 ± 0.1	0.31
0	100	20	14.3 ± 0.2	
20	80	20	14.8 ± 0.2	
40	60	20	15.0 ± 0.3	
60	40	20	16.0 ± 0.2	
80	20	20	15.9 ± 0.1	
100	0	20	16.7 ± 0.2	

those obtained in wheat straw mixtures. The decrease in pellet strength with the addition of ground rapeseed straw was not as high as with the addition of wheat straw. We obtained a minimum strength value of 0.32 MPa in the mixture with an 80% addition of ground rapeseed. In the case of wheat straw, we observed a decrease in the strength of the pellets with increasing moisture content and an increase in strength with increasing compaction pressure.

Table 7 presents the determined HC and ash content values. The HC values ranged from 14 MJ/kg to 18.5 MJ/kg and decreased with an increase in the proportion of straw in the mixture. We obtained a minimum HC value of 14.3 MJ/kg for pure straw, and a maximum HC value of 18.5 MJ/kg for sawdust with 8% moisture content. As expected, an increase in moisture content resulted in an approximate 10% decrease in the HC for all tested materials. The ash content values increased with the addition of straw, and we obtained higher ash content in rapeseed straw mixtures.

4. Discussion

We investigated the effect of compaction pressure, moisture content and the proportion of pine sawdust in mixtures of wheat and rapeseed straw with respect to the density, mechanical strength and durability of produced pellets. The pellets were made from the biomass of plants very common in the local region. Experiments similar to those reported in this article were previously performed by Liu et al. [21] for bamboo and rice straw, with materials mixed with the same proportions. The results obtained in our study show the influence on the technological factors of strength, durability and the dimension of the agglomerates produced from raw materials in a single unheated die. These results may be used to establish the optimum composition of material to obtain durable pellets in real technological processes. Information is scant regarding the compaction characteristics of rapeseed straw in pellets production, compared to the availability of studies on other kinds of sawdust and straws. Investigations similar to ours have been reported by Serrano et al. [24] for mixtures of barley straw with the addition of a small amount of pine sawdust (2, 7 and 12%) compacted in a heated die. In the case of the heated die, a certain amount of water evaporated during pelletization. In our tests, we studied the influence of moisture content and conducted tests at moisture contents of 8% and 20%, which were comparable to the values adopted by Lee et al. [20] in their tests of tulipwood and larch sawdust at moisture contents ranging from 9% to 13%.

The durability values determined by the method used in this study produced different results and higher standard deviations than those of a comparative study using different methods to determine durability [6]. The durability values obtained in our study, ranging from 40% to 78%, were lower than those obtained by the other researchers, despite the same moisture content range and compaction pressures. This is probably due to the lack of heating of the cylindrical die. Our results show that an increase in pellet height results in a decrease in density, probably because the longer pellets are less compact, and have more voids and cracks. Serrano et al. [24] found that the 95.5% durability of barley straw pellets increased to 97%–98% with the addition of small quantities of pine sawdust up to 12%. In pellets made of a mixture of bamboo and rice straw in weight proportions similar to those tested in this study, Liu et al. [21] reported an increase in durability with an increase in the content of rice straw. The authors also found that durability was not influenced by moisture content, which was in direct contrast to the findings reported by Serrano et al. [24], who observed a strong increase in durability with an increase in moisture content in compressed biomass. Lee et al. [20] found that an increase in moisture content from 9% to 13% did not significantly influenced durability, which agrees with results of our study. However, unlike our findings, these authors also observed an increase in durability with an increase in moisture content from 7% to 9%. Variation in the results from various laboratories with respect to the influence of moisture content may be a result of differences in the conditions in cultivation, different apparatuses producing the pellets (heated or unheated die) or differences in methods used to determine the characteristics. We consider that more studies by different researchers will be necessary in order to draw firm conclusions.

Regarding the relationship between density and durability, in this study, we found no relationship between these two parameters, which corroborated the findings reported by Temmerman et al. [29]. While our results point to a correlation between durability and the strength of the pellets, the methods used to determine these two characteristics differed, so there is no simple method to characterize one by the other. Nevertheless, durability and the strength of the pellets decreased with an increase in the addition of straw in the mixtures.

The density of pellets, ranging from 600 kg/m^3 to about 800 kg/m^3, is in agreement with previously reported results, e.g., by Gilbert et al. [8]. These authors compressed cut switch grass and straw and obtained pellets with densities from approximately 200 kg/m^3 to nearly 800 kg/m^3. The density of straw pellets obtained by these authors for 95 MPa of compaction pressure was comparable to the results obtained in this study for a compaction pressure of 120 MPa. Shaw et al. [25] reported higher pellet density values for untreated and exploded poplar wood and wheat straw grinds compacted at 120 MPa. The authors also stated that in the majority of tests an increase in moisture content resulted in a decrease in pellet density. The authors observed a strong influence of compaction pressure on pellet density in a range up to 60 MPa, which was consistent with the results presented here. The authors obtained a 300% increase in density with an increase in compaction pressure, which was much higher than the values obtained in this study. The probable reason of these discrepancies were differences in the tested materials. The densities obtained in our project were also lower than those obtained by Serrano et al. [24] for barley straw mixed with pine sawdust. Values reported in that study were approximately 1.5 times higher than our results, which is probably due to difference in the equipment used—Serrano et al. [24] used an industrial-scale machine. In our project, pellet density decreased with increasing moisture content, and these findings corroborated those of Serrano et al. [24], who reported a 20% decrease in density. However, the density values obtained in our experiments were comparable to those obtained by Lee et al.

[20] for pellets produced in a single-piston pelletizer. Lu et al. [22] compacted wheat straw under 126 MPa in a single 95 °C heated die and obtained a density of 996.49 kg/m^3, which was close to that determined in our study. The compaction of mixtures of bamboo and rice straw by Liu et al. [21] also gave results close to ours. Adapa et al. [1] presented compaction characteristics of four kinds of straw, and obtained densities ranging from about 850 kg/m^3 to 924 kg/m^3 for wheat straw pellets, which are also similar to our density results.

The strengths of the pellets obtained in our project were lower than those reported by Lu et al. [22] for wheat straw-binder pellets (from 0.84 MPa to 1.63 MPa), and were close to the 0.81 MPa obtained for wheat straw pellets by Kashaninejad and Tabil [18]. The mechanical strength of the pellets was influenced by the proportion of materials in the mixtures. The strength values determined in a range from 0.2 MPa to approximately 0.6 MPa were comparable with the mechanical strength of pellets of cut switch grass and straw reported by Gilbert et al. [8], for which strengths up to 0.4 MPa were obtained for material compacted with pressures up to 55 MPa. These authors found tensile strength to increase up to 500% with an increase in pressure from 10 MPa to 55 MPa, while in our tests increases in the strength of the pellets did not exceed 60%.

The results we obtained in this project fall within the ranges of values recommended by standard ISO 17225 for the density of pellets and their heating value. Regarding our results for lower moisture content, the heating value was higher than those recommended by ISO 1225 for woody biomass (≥16.5 MJ/kg) and non-woody biomass (≥14.5 MJ/kg). For higher moisture contents of the tested mixtures, the heating value of the produced pellets was satisfactory. With respect to the density of pellets obtained in our project, this parameter was higher than 600 kg/m^3, as recommended by standards, but the durability of the pellets was distinctly lower than the 96%–97.5% recommended in ISO 17225.

Future investigations of biomass compaction should consider heating the cylindrical die as this may improve the durability of the produced pellets. Filling the die in pairs of smaller batches may also improve the quality of the produced pellets.

5. Conclusions

We performed a series of experiments on pure sawdust and sawdust blended with ground wheat or rapeseed straw in various proportions. We can draw the following conclusions:

- The mechanical parameters of pellets and their heats of combustion were found to decrease with an increase in the proportion of straw in the blends.
- Mixtures of pine sawdust with ground wheat and rapeseed straws could be used in the local production of pellets.
- The poured density of all experimental materials decreased with an increase in moisture content.
- The most pronounced increase in tapped density was observed in mixtures of sawdust and ground wheat straw at a lower moisture content (8%).
- The addition of ground rapeseed straw resulted in an increase in the flowability of both dry (8%) and moist (20%) material. This mixture was classified as having good flowability, while the others exhibited moderate or poor flowability.
- The density of pellets decreased with an increase in the percentage of the two kinds of straw in mixtures. The density of pellets made of moist (20%) mixtures of sawdust and wheat straw was lower than those made of dry (8%) mixtures. We observed no influence of moisture content on the biomass mixture with respect to the addition of rapeseed straw to sawdust. An increase in compaction pressure resulted in an increase in pellet density.
- The mean values of drop resistance decreased with the addition of wheat starch and the decrease was lower for a higher moisture content and compaction pressure. In mixtures of sawdust with ground rapeseed straw, we obtained pellets of higher durability and drop resistance. An increase in moisture content resulted in an increase in drop resistance, and a higher compaction pressure resulted in higher drop resistance.
- The swirled durability of mixtures with rapeseed straw was not dependent on the percentage contribution of rapeseed straw and moisture content. Only at a higher compaction pressure did we observe an increase in durability.
- The strength of the pellets decreased with the addition of ground straw. In mixtures of pine sawdust with rapeseed straw, we found a higher pellet strength. We also observed a decrease in strength with increasing moisture content and an increase with increasing compaction pressure.
- The heat of combustion values of both mixtures were similar. We observed a decrease in the heat of combustion with an increase in the percentage contribution of straws in mixtures. We obtained a minimum heat of combustion value in pure straws. As expected, an increase in moisture content resulted in an approximately 10% decrease in the heat of combustion in ground wheat straw mixtures and rapeseed straw mixtures.
- The addition of straws resulted in an increase in ash content, and we obtained higher ash contents in mixtures with rapeseed straw.

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