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Energy Consumption and Quality of Pellets Made of Waste from Corn Grain Drying Process

Grzegorz Maj , Paweł Krzaczek *, Wojciech Gołębiowski , Tomasz Słowik , Joanna Szyszlak-Bargłowicz and Grzegorz Zając

Department of Power Engineering and Transportation, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland; grzegorz.maj@up.lublin.pl (G.M.); wojciech.golebiowski@up.lublin.pl (W.G.); tomasz.slowik@up.lublin.pl (T.S.); joanna.szyszlak@up.lublin.pl (J.S.-B.); grzegorz.zajac@up.lublin.pl (G.Z.)

* Correspondence: pawel.krzaczek@up.lublin.pl; Tel.: +48-81-5319720

Abstract: The aim of this study was to assess the possibility of managing the waste resulting from the corn grain drying process as a biofuel characterized by low energy consumption in the compaction process and to evaluate the quality of the pellets made of this waste. The waste was agglomerated in the form of corn grain (CG), husks (CH), and cobs (CC), and their mixtures were prepared in a 4:1 volume ratio. The results of the analyses showed that CH was the most advantageous material for agglomeration due to the process's low energy consumption (47.6 $Wh \cdot kg^{-1}$), while among the prepared mixtures, CC-CH was the most energy-efficient (54.7 $Wh \cdot kg^{-1}$). Pellets made of the CH-CC mixture were characterized by good quality parameters, with a satisfactory lower heating value (13.09 $MJ \cdot kg^{-1}$) and low energy consumption in the agglomeration process (55.3 $Wh \cdot kg^{-1}$). Moreover, data analysis revealed that the obtained pellets had density (1.24 $kg \cdot dm^{-3}$) and mechanical durability (89%), which are important in their transport and storage. The findings of this study suggest that the use of waste from the corn grain drying process, in the form of pellets, may allow obtaining granules with different quality.

Keywords: corn grain; drying waste; pellets; energy consumption; pellet quality

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1. Introduction

Biomass derived from the agricultural sector can primarily serve as a source of food and fodder, as well as raw material for the production of bioenergy [1–4]. The direct use of crops for energy purposes is promoted by the increasing demands of global and local food and energy markets, which are often regulated by authorities [5,6]. However, due to the sustainable development of the agricultural and energy sectors [7], research and industrial projects are being carried out to enable the extensive use of inedible plant parts [8,9] and to minimize residues [10,11] and residual biomass [12,13]. In recent years, there has been an increasing interest in the use of waste generated during the harvest of biomass, as well as from raw plant material processing and food or feed production, to meet specific quality or technological requirements [14–16]. On the other hand, legal regulations have been imposed, defining the parts of plants that can be used for energy purposes and the quality standards that should be fulfilled by the fuels obtained from plant parts [11,17,18]. The thermal conversion of biomass is associated with waste combustion [19,20] and makes use of other thermochemical processes [21,22], such as pyrolysis, gasification, or torrefaction [23,24].

Among crops, the largest amount of waste during agricultural production [20,25] or postharvest processes [26] can result from corn [27,28]. Corn has a high yield potential and a variety of applications [29–31]. The increase in corn production observed in recent years is mainly due to the rising demand for biofuel production in the industrial processing sector [32,33].

Corn grains are of different shapes. The harvesting of these grains, usually with the use of a combine harvester, results in impurities and damaged grain [34,35]. Because the harvested grains have a high content of moisture, the process of drying them is critical [36]. Fungal spores can rapidly form in impurities such as soil, dust, and plant residues [37]. Therefore, before storage, the harvested grains should be thoroughly cleaned and dried [38] in order to allow the grains to achieve the desired level of moisture and purity for their application in the agri-food industry [39]. However, the process of cleaning and drying leads to the generation of waste in different forms (i.e., corn cobs, damaged grains, and husks) [37,40]. Considering their energy potential, these waste residues can be used at their place of origin to improve the energy and economic balance of drying plants. Moreover, apart from the waste resulting from the drying process, attempts have been made to obtain biomass residues in the form of corn stover for energy applications [41,42]. For instance, a study analyzed the possibility of acquiring residues from corn cob chaff directly in the process of harvesting [34]. However, the management of a large amount of waste biomass derived from these processes, as well as its use by drying plants, is challenging.

Furthermore, corn residues are considered a problematic biowaste due to their low density and high management, transport, and storage costs. The most popular approach to improve the energy efficiency of the use and management of different forms of plant waste or their mixtures is to increase the density of the biomass [6,43]. Densification is often carried out by the process of pelletizing [44] or briquetting into the form of solid fuel (pellets and briquettes) [45–47] or, in the case of dusty agri-food waste, by non-pressure agglomeration [48,49]. Pressure agglomeration, as well as pelletizing and briquetting, allows reducing the volume of waste biomass and improves its properties as a solid biofuel [50]. However, some works have demonstrated technical problems, in that the production of fuel pellets from post-production corn waste is limited by technical issues [36,51].

The cost of the granulation process (pressure agglomeration), its efficiency and energy consumption, and the quality of the obtained product are closely related to the raw material, apparatus, and process parameters [52]. In the search for the most advantageous process parameters, the energy efficiency [53] and durability of the obtained granules are considered as key factors, as they play an important role in the transport and storage of these granules and their applications (e.g., animal feed in the case of granulated feed) [44].

In an earlier study, the authors [37] determined the physicochemical properties of residues resulting from the corn drying process, and their mixtures were determined as potential biofuel. In addition, Zając et al. [54] examined the effect of the chemical composition of ash formed from the combustion of waste biomass from the corn grain drying process, analyzed the possibility of its use in fertilization, and estimated the potential risk associated with its introduction into the environment. The aim of the present study was to assess the possibility of managing the waste resulting from the corn grain drying process as a biofuel characterized by low energy consumption in the compaction process and to evaluate the quality of the obtained pellets. Parameters such as density, bulk density, kinematic durability, energy density, and granule length and diameter were taken into account in the assessment. The working parameters of the tested materials were adopted in accordance with the aim of the study. The materials were subjected to compaction immediately after pre-collection, and only corn cobs were milled.

An important goal of this study was to obtain information on energy consumption during pelleting under the conditions of a potential pellet producer and to analyze how waste generated in corn dryers can be utilized for energy purposes with the lowest effort and cost. Another purpose of this study was to demonstrate the potential of waste management for energy purposes, which is in line with the circular economy trend.

2. Materials and Methods

The research material was waste generated during the corn drying process. The waste used in the study was from the 2018 harvest from drying plants in Lublin (Poland). It was analyzed in different forms:

1 Remains of corn cobs without grain—corn cobs (CC);
2 Grain residues from the process of drying and cleaning of corn kernels—corn grains (CG);

3 Husks of corn grains—corn husks (CH);
4 As mixtures of the above materials in a 4:1 (*v*/*v*) ratio:
5 Corn cobs and corn husks (CC-CH);
6 Corn grains and corn cobs (CG-CC);
7 Corn cobs and corn grains (CC-CG);
8 Corn husks and corn grains (CH-CG);
9 Corn husks and corn cobs (CH-CC);
10 Corn grains and corn husks (CG-CH).

The mixtures were prepared in a volume ratio (*v*/*v*), which allowed simplifying their preparation for other processes, such as pelleting, and avoiding the need to weigh material for fuel preparation. On the other hand, the use of mass proportions would require additional work for biofuel preparation, which would reduce the profitability of waste disposal. The characteristics of the materials used are described in detail in the paper by Maj et al. [37].

The corn cobs required grinding to 3 mm fractions before pelletizing. Prior to agglomeration, the moisture content of the material (Table 1) was assessed by thermogravimetry in accordance with EN ISO 18134.

Table 1. Moisture content of raw materials from corn grain drying process.

Parameter	Unit	Material								
		CC	CC-CG	CC-CH	CG	CG-CC	CG-CH	CH	CH-CG	CH-CC
M ± S_x	(%)	28.32 ± 0.21	28.02 ± 0.36	29.20 ± 0.59	27.23 ± 0.12	27.89 ± 0.90	28.96 ± 0.42	30.01 ± 0.32	27.67 ± 0.33	29.68 ± 0.32

M—moisture content; S_x—standard deviation.

The complete research procedure is illustrated in Figure 1.

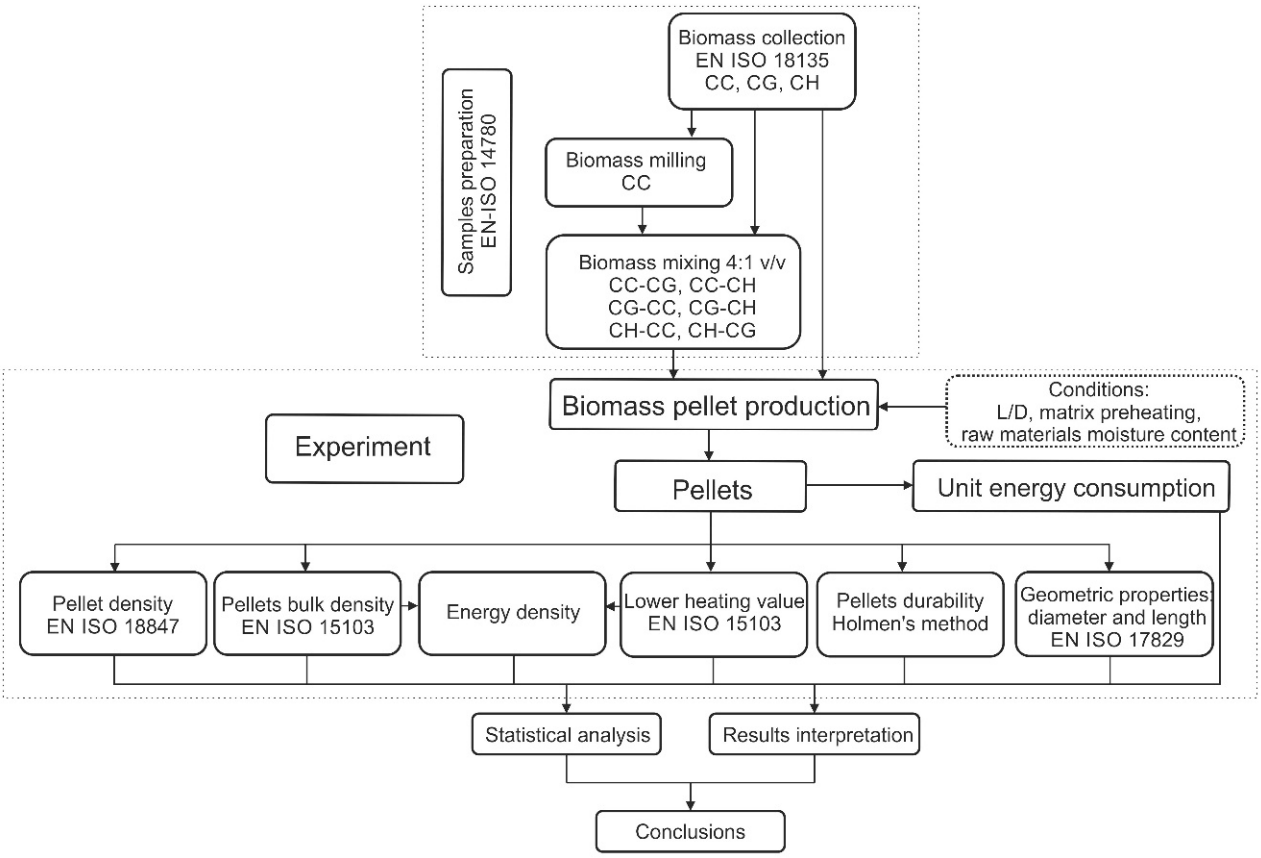


Figure 1. Schematic illustration of the research procedure.

The analyzed material was granulated using a granulator with a rotary flat matrix (BRICOL ZSJ25, Człuchów, Poland), and the maximum yield of granules was up to 100 kg·h^{-1}. The flat matrix had channels with a diameter (D) of 6 mm and a length (L) of 30 mm (L/D = 5.0). The matrix worked at 260 rpm, and the material flow was 1.6 kg·min^{-1}. Granulation tests began after the matrix was preheated to 85 °C. The temperature of the matrix was monitored throughout compaction and maintained constant (±5 °C).

During granulation, the total energy consumption EC (Wh·kg^{-1}) was quantified using a power analyzer (KYORITSU KEW6310) in order to determine the energy used for maximum granule production. The data from the analyzer were evaluated in KEW PQA MASTER software.

The pellets obtained from the granulation process were assessed for their physical characteristics and quality. Laboratory samples were collected for measurements in accordance with ISO 18135 and prepared for testing in accordance with ISO 14780. The mean value of at least three replications was calculated.

Geometrical parameters (diameter Di (mm) and length L (mm)) were measured in accordance with ISO 17829. Pellet samples with a minimum mass of 100 g were randomly chosen for the measurement of these parameters. All the parameters of the pellet were determined in triplicate, using a caliper with a measurement accuracy of ±0.1 mm, and the mass of the pellets was determined using a Radwag PS.6000.3Y laboratory balance, with a measurement accuracy of ±0.01 g.

Pellet density (D, kg·m^{-3}) was determined in accordance with ISO 18847 by the hydrostatic method, using a density determination kit for solids and liquids (KIT-85, Radwag, Radom, Poland). The kit included a Radwag X3.Y analytical balance with a measurement accuracy of ±0.0001 g. A mixture of water and a wetting agent (Triton X-100) at a concentration of 1.5 g·L^{-1} was used as the reference liquid. The mean value of five replications was calculated.

The bulk density (DB kg·m^{-3}) was determined in accordance with ISO 17828. This parameter was measured using a 5:l vessel. The mean value of five replications was calculated.

The mechanical durability (DU%) of the pellets was measured using a Ligno pellet tester (NHP100, Tekpro, Norfolk, UK). For the Holmen test, samples of 100 g of pellets, collected after 60 s of sieving through a 2.5 mm sieve, were pneumatically conveyed around in a closed cylinder loop for 1 min. The DU was calculated as a ratio of the mass of pellets remaining in the chamber to the initial sample mass. The mean value of five replications was calculated.

The energy density ED (GJ·m^{-3}) of the pellet samples was determined by Equation (1).

$$ED = BD\ LHV \tag{1}$$

where:

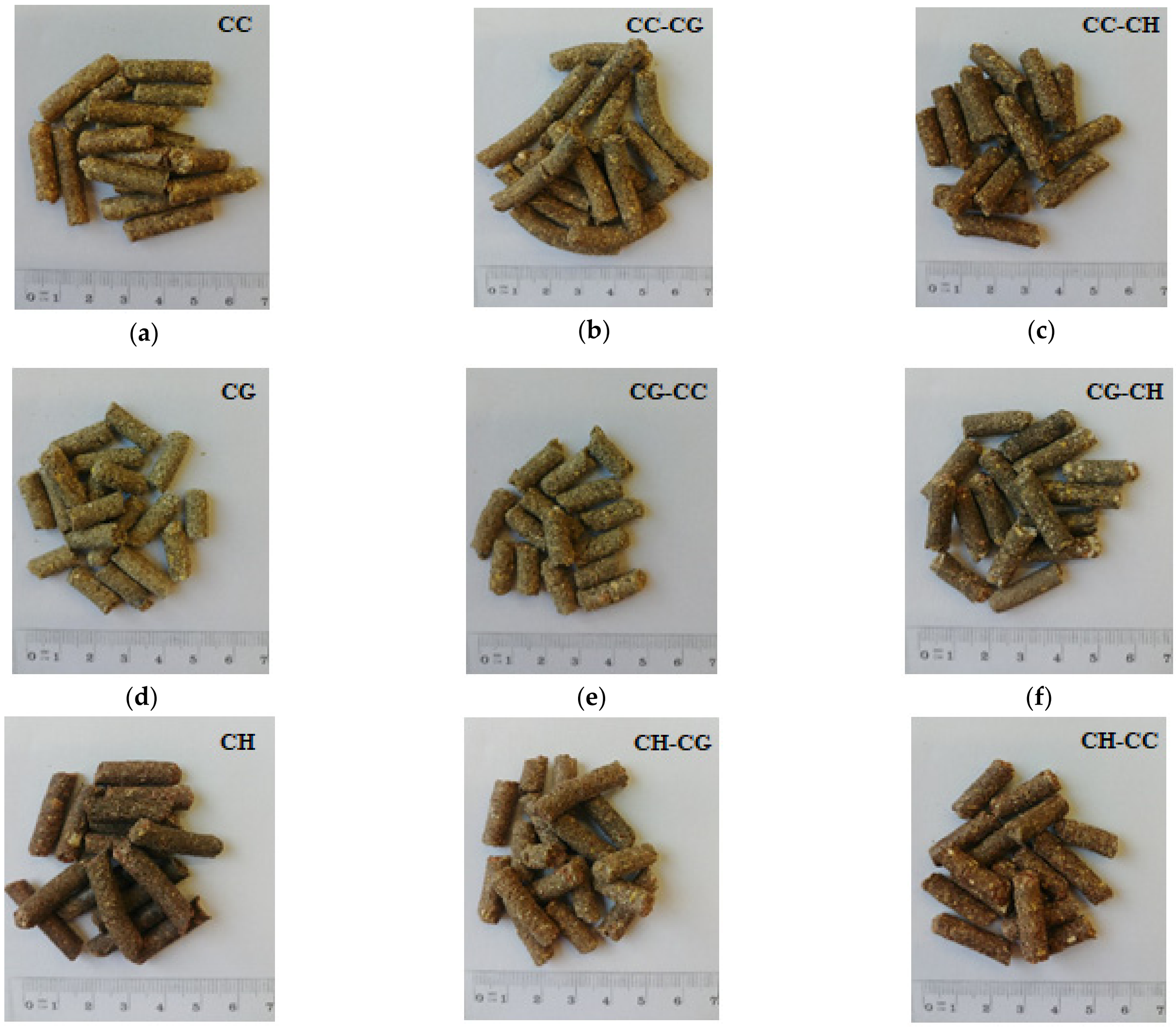
LHV is the lower heating value (GJ·kg^{-1});

BD is the bulk density (kg·m^{-3}).

The obtained results were subjected to statistical analysis. The normal distribution of the examined traits was verified by the Shapiro–Wilk test. The influence of the type of material on the individual examined traits was analyzed using one-way analysis of variance. The homogeneity of variance was checked by Levene's test, and significant differences between the tested groups of traits were checked by Tukey's honest significant difference (HSD) test. Statistical analysis was performed at a significance level (α) of 0.05.

3. Results and Discussion

Figure 2 shows the images of pellets obtained in the compaction process. Table 2 presents the results of the qualitative assessment of the obtained pellets.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**) (**h**) (**i**)

Figure 2. Pellets obtained from individual materials and their mixtures: (**a**) corn cobs (CC), (**b**) corn cobs and corn grains (4:1, *v*/*v*) (CC-CG), (**c**) corn cobs and corn husks (4:1, *v*/*v*) (CC-CH), (**d**) corn grains (CG), (**e**) corn grains and corn cobs (4:1, *v*/*v*) (CG-CC), (**f**) corn grains and corn husks (4:1, *v*/*v*) (CG-CH), (**g**) corn husks (CH), (**h**) corn husks and corn grains (4:1, *v*/*v*) (CH-CG), and (**i**) corn husks and corn cobs (4:1, *v*/*v*) (CH-CC).

Table 2. Qualitative assessment of pellets obtained from residues from corn grain drying process.

Parameter	Unit	Material									*p*-Value
		CC	CC-CG	CC-CH	CG	CG-CC	CG-CH	CH	CH-CG	CH-CC	
$D \pm S_x$	($kg \cdot dm^{-3}$)	$1.14^{a,b} \pm 0.00$	$1.15^{b} \pm 0.01$	$1.12^{a} \pm 0.01$	$1.26^{c} \pm 0.01$	$1.24^{c} \pm 0.01$	$1.29^{d} \pm 0.00$	$1.35^{f} \pm 0.02$	$1.29^{d} \pm 0.01$	$1.24^{c} \pm 0.03$	<0.01
$BD \pm S_x$	($kg \cdot m^{-3}$)	$547.9^{c} \pm 1.2$	$527.2^{b} \pm 2.8$	$444.6^{a} \pm 0.5$	$603.1^{f} \pm 3.9$	$551.5^{c} \pm 4.2$	$608.1^{f,g} \pm 0.2$	$610.9^{g} \pm 2.0$	$586.8^{e} \pm 3.3$	$566.9^{d} \pm 1.2$	<0.01
$DU \pm S_x$	(%)	$88.65^{d} \pm 0.01$	$83.69^{c} \pm 0.02$	$93.52^{e} \pm 0.04$	$57.97^{a} \pm 0.02$	$57.38^{a} \pm 0.02$	$78.33^{b} \pm 0.02$	$96.19^{f} \pm 0.01$	$77.39^{b} \pm 0.02$	$89.64^{d} \pm 0.01$	<0.01
$Di \pm S_x$	(mm)	$6.25^{a,b,c} \pm 0.05$	$6.40^{c,d} \pm 0.16$	$6.38^{b,c,d} \pm 0.03$	$6.20^{a} \pm 0.10$	$6.30^{a,b,c,d} \pm 0.10$	$6.35^{a,b,c,d} \pm 0.05$	$6.22^{a,b} \pm 0.13$	$6.46^{d} \pm 0.24$	$6.43^{d} \pm 0.03$	<0.01
$L \pm S_x$	(mm)	$26.1^{c} \pm 4.3$	$37.0^{d} \pm 6.5$	$22.2^{a,b,c} \pm 2.9$	$18.5^{a} \pm 2.7$	$19.6^{a} \pm 2.5$	$19.7^{a} \pm 2.3$	$24.7^{b,c} \pm 3.4$	$20.1^{a,b} \pm 2.2$	$22.9^{a,b,c} \pm 2.4$	<0.01

D—pellet density, BD—bulk density, DU—mechanical durability, D_i—diameter of pellets, L—length of pellets, and S_x—standard deviation; mean values with the same letter in a row are not significantly different at $p < 0.05$ according to Tukey's HSD test.

The results of the quality analysis of the pellets produced from residues resulting from the corn grain drying process (Table 2) showed that the pellet density ranged from 1.12 to 1.35 $kg \cdot dm^{-3}$. This confirmed that the obtained pellets met ÖNORM M 7135, DIN 51731, and DIN Plus standards. The pellets made of CC, as well as of the CC-CH and CC-CG mixtures, were characterized by the lowest density, while the pellets made from CH had the highest density (17% higher than the lowest value). The results of the statistical analysis revealed significant differences in all the assessed traits between the analyzed raw materials. Regarding the density of the obtained pellets, similarities were found between CC and CC-CG, as well as among CC, CC-CH, and CG, and CG-CC, CH-CC, CG-CH, and CH-CG.

Jiang et al. [55] obtained pellets of lower densities (0.863–1.217 kg·dm^{-3}) from rice straw, Chinese fir, and camphor waste, sewage sludge, and their mixtures. Similarly, Zawiślak et al. [16] obtained pellets of lower densities (1.03–1.15 kg·dm^{-3}) from soybean, pea, chamomile, and birch sawdust waste and their mixtures. Tan et al. [56] also obtained pellets of lower densities (1.03–1.11 kg·dm^{-3}) from *Camellia oleifera* Abel. shell. In addition, Zhang T. et al. [11] determined lower density values (0.87–1.05 kg·dm^{-3}) for other types of waste, such as apple tree residues and corn straw, mixed with frying oil in different proportions. By contrast, using various mixtures of paper, wood, and organic and plastic waste, Rezaei et al. [57] obtained pellets of higher densities, ranging from 1.15 up to 1.5 kg·dm^{-3}. Using garden waste, Pradhan et al. [2] produced pellets with a wide range of densities (0.5–1.4 kg·dm^{-3}), depending on the moisture content of the compacted waste biomass. Yang et al. [24] obtained pellets characterized by lower values of density (0.6–1.0 kg·dm^{-3}) from a mixture of corn straw and big bluestem, but the process of pelletizing was simultaneously supported by the process of torrefaction in their study. From commonly used wood waste, Garcia et al. [58] obtained pellets with comparable densities of 1.01–1.27 kg·dm^{-3}. On the other hand, Alam et al. [14] obtained pellets of high densities, in the range of 1.03–1.27 kg·dm^{-3}, from medical waste and plastics, in admixture with rice straw after the pyrolysis process. Kirsten et al. [59] obtained pellets with comparable densities, in the range of 1.18–1.29 kg·dm^{-3}, from hay. In turn, by briquetting the remains of corn cobs, Orisaleye et al. [52] obtained pellets with densities in the range of 1–1.4 kg·dm^{-3} by varying the process parameters. These findings suggest that the densities of the pellets tested in this study did not differ from the values determined for pellets made from the biomass of plant origin, and thus, the tested material can be used in the agglomeration process.

The bulk densities of the studied pellets varied widely, in the range of 444.6–610.9 kg·dm^{-3}. The lowest bulk density value was observed for pellets made from the CC-CH mixture, while the highest value was obtained for pellets made from the CH mixture (27% higher than the lowest value). In terms of bulk density, the pellets made of CG, CH, and the CG-CH mixture met only the SS 18 71 20 standard. The results of the statistical analysis showed similarities in bulk density between the CG and CG-CH pellets, as well as between the CH and CG-CH pellets.

The values of bulk density recorded in this study were slightly lower than those determined for wood biomass in the studies by Garcia et al. [58] (470–671 kg·dm^{-3}) and Stasiak et al. [60] (732 $\pm$ 10 kg·dm^{-3}). Furthermore, the study by Alam et al. [14] reported higher density values for the mixtures of biomass with various types of waste (540–737 kg·dm^{-3}). Moreover, Djatkov et al. [51] determined the bulk density of corn waste to be in the range of 547–719 kg·dm^{-3}, which was similar to the values determined by Miranda et al. [40] for corn cob waste (525–685 kg·dm^{-3}). On the other hand, Niedziółka et al. [61] obtained comparable bulk density values for maize straw pellets (561–572 kg m^{-3}). Higher values of bulk density were reported by Keppel et al. [62] for various cereal and wood straw waste materials (520–718 kg·dm^{-3}). Kirsten et al. [59] also obtained high bulk density values (575–660 kg·dm^{-3}) for hay pellets. In turn, lower bulk density values were observed by Niedziółka et al. for wheat straw pellets (386–420 kg·m^{-3}) [61], and by Tan et al. for pellets made from an oil-tea processing plant (359–442 kg m^{-3}) [56]. By contrast, comparable bulk density values were determined by Zawiślak et al. [16] for soybean, pea, chamomile, and birch sawdust waste and their mixtures (489–606 kg·m^{3}).

The analysis of the mechanical strength of pellets made of CC, CG, and CH, as well as their mixtures, indicated high diversity (57.38–96.19%). The highest mechanical strength was recorded for the pellets made of CH, which was over 1.5-fold higher than that recorded for the pellets made of CG-CC. The results of the statistical analysis showed significant differences in mechanical strength between the studied materials.

It was found that the durability of CG grain waste, and its mixtures with cobs and husks, was much lower compared to other materials and mixtures. The addition of CG reduced the durability of the pellets, which may be due to the chemical composition of this material and its physical properties, as well as mineral impurities, as indicated by other authors [51,54,62]. For further comparison of the obtained results with those of other works, mixtures with an undamaged grain base were considered. Comparable values of durability in the process of pelletizing, aided by torrefaction, were reported by Yang et al. [24] for corn straw and big bluestem (71–90.5%). Similarly, Ghasemi et al. [63] observed a wide range of durability (70–95%) for pellets made from different types of biomass. In turn, Ríos-Badrán et al. [18] obtained pellets with durability at a level of 95% and higher for rice husks, and in the range of 89.5–92% for a wheat husk and straw mixture, which were similar to the values determined by [16] for soybean, pea, chamomile, and birch sawdust waste and their mixtures (90.2–97.1%). In the study by Alam et al. [14], pellets obtained from a mixture of rice straw and medical waste were also characterized by a durability of 91.1–98.3%. Comparable values of durability were obtained by Ishii and Furuichi [64] for pellets made of rice straw. Niedziółka et al. [61] found that pellets obtained from rape, wheat, or maize straw had high durability at a level of 95.4–98.9%. Kirsten et al. [59] also reported that the durability of hay pellets was 95–97.5%. Similar high durability values, at a level of over 99%, were obtained by Zhang T. et al. [11] for a mixture of wood waste from apple trees, corn straw, and waste cooking oil, while Garcia et al. [58] reported durability values above 97% for various types of wood waste. For mixtures with different proportions of wood sawdust from leaf residue and ground nut shells, Rajput et al. [65] obtained widely varying durability values, ranging from 82.6 to 97.3%. However, for waste materials intended for reuse, such as cardboard, wood, and various types of plastics mixed with organic waste as a binder, Rezaei et al. [57] obtained higher durability values of 93.1–99.9%. Thus, it can be concluded that pellets produced from mixtures have low durability, which was confirmed by the results presented in Table 2 and by the studies of Zawiślak et al. [16], Yang et al. [24], and Alam et al. [14].

The evaluation of the length of the obtained pellets showed that the pellets had lengths of 18.5–37 mm. The shortest pellet was obtained from CG, and the longest from the CC-CG mixture. The lengths of the pellets obtained from CG, CG-CC, CG-CH, CH-CG, and CC-CH were similar. The pellets obtained in this study differed significantly in length relative to each other, while in the study by Ríos-Badrán et al., the pellets made from rice husk and its mixture with wheat straw had similar length values of 24–26 mm [18]. However, the introduction of mixtures of different types of biomass as material for pelletizing increases the differences in obtained test results, as observed in the study by Zawiślak et al. [16], in which lengths ranging from 24.4 to 31.3 mm were obtained. On the other hand, Garcia et al. [58] found that pelletizing wood waste in combination with food industry waste allowed achieving a smaller length distribution of pellets, in the range of 21.7–27.1 mm. By contrast, much shorter lengths of pellets, with slight differences, were obtained by Tan et al. [56] from waste in the form of *C. oleifera* Abel. shell (16.1–16.8 mm).

The pellets made of homogeneous materials were characterized by similar diameters, ranging from 6.20 (for CG) to 6.25 mm (for CC). The pellets obtained from the mixtures of the tested materials had larger diameters than those made from base materials. Pellets with the highest diameters were obtained from the mixtures containing husks with other materials, while slightly lower values were obtained for the pellets made from mixtures based on CC. The increase in the diameters of the pellets can be attributed to the content of the fibers in agglomerated particles, which cause elasticity and expansion after the agglomeration process. An analogous conclusion regarding the influence of the applied biomass on the diameter of pellets was presented by Ríos-Badrán et al. [18], who obtained a diameter of 6.01 mm for pellets from rice husks, which was lower compared to that of the pellets made from corn husks.

However, the diameters of pellets obtained from a mixture of rice husks with wheat straw were similar (6.30–6.38 mm) to those of the pellets made from corn waste. Due to their elasticity, both corn husks and wheat straw form pellets with larger diameters. After the agglomeration process, these materials expand, which increases the diameter of the pellets. Similar values of diameter were obtained for pellets of wood and food waste in the study by Garcia et al. [58] (6.18–6.47 mm). Zawiślak et al. [16] obtained pellets with higher diameters from waste materials pelletized in different proportions (8.30–8.50 mm) using an 8 mm matrix. However, when using a homogeneous material containing cellulose fibers, the content of lignin and moisture in the material is important. In the study by Tan et al. [56], when *C. oleifera* Abel. shell was pelleted using a 7 mm matrix, pellets with diameters of 7.07–7.18 mm were obtained, while pellets of higher diameter values were obtained from non-humidified materials. The results of the statistical analysis showed similarities in the diameter of the obtained pellets, whereas the pellets from CG and CH-CC showed significant differences in this parameter.

Table 3 shows the results of the evaluation of energy consumption for pellet production from corn grain drying residues.

Table 3. Results of the evaluation of energy consumption for the process of pellet production from corn grain drying residues.

Parameter	Unit	Material									*p*-Value
		CC	CC-CG	CC-CH	CG	CG-CC	CG-CH	CH	CH-CG	CH-CC	
LHV * ± S_x	($MJ \cdot kg^{-1}$)	$14.94^{d} \pm 0.01$	$13.70^{c} \pm 0.04$	$13.07^{b,c} \pm 0.64$	$13.23^{b,c} \pm 0.17$	$13.36^{b,c} \pm 0.04$	$12.90^{b} \pm 0.01$	$9.69^{a} \pm 0.09$	$10.19^{a} \pm 0.06$	$13.09^{b,c} \pm 0.01$	<0.01
EC ± S_x	($Wh \cdot kg^{-1}$)	$62.4^{c} \pm 1.1$	$69.3^{e} \pm 0.8$	$54.7^{b} \pm 1.3$	$78.6^{g} \pm 0.9$	$73.8^{f} \pm 0.5$	$65.7^{d} \pm 0.7$	$47.6^{a} \pm 0.3$	$68.8^{e} \pm 0.8$	$55.3^{b} \pm 1.4$	<0.01
ED ± S_x	($GJ \cdot m^{-3}$)	$8.19^{g} \pm 0.02$	$7.22^{c} \pm 0.04$	$5.81^{a} \pm 0.01$	$7.98^{f} \pm 0.05$	$7.37^{d} \pm 0.06$	$7.84^{e} \pm 0.00$	$5.92^{b} \pm 0.02$	$5.98^{b} \pm 0.03$	$7.42^{d} \pm 0.02$	<0.01

* Maj et al. [37], LHV—lower heating value, EC—energy consumption, ED—energy density, and S_x—standard deviation; mean values with the same letter in a row are not significantly different at $p < 0.05$ according to Tukey's HSD test.

The results of the analysis of energy consumption during pelletizing showed significant differences in the energy input required to obtain pellets, which ranged from 47.6 to 78.6 $Wh \cdot kg^{-1}$. The lowest energy demand was found for pellet production from CH, while CG was the most energy-consuming material in the process of pressure agglomeration, for which the increase in energy input exceeded 65%. It should be noted that the addition of corn husks positively influenced the energy consumption of the pelletizing process. In the case of the pelletizing of the CC and CH mixture, the energy consumption was lower by 12%, and for the CH and CG mixture, it was lower by 16%. In turn, the addition of damaged grains to cobs increased the energy demand by 11%, and to husks, by over 40%. This increase in energy consumption was primarily due to the properties of the biomass used. When subject to pressure, flexible husks adopt the shape of other molecules (CC and CG), and the friction between agglomerated particles is also lower due to the husks' smooth surface. In the case of grains, individual particles are uneven and sharp [37], often contaminated with mineral substances (dust and soil remnants), and clearly visible, which results in increased friction between biomass particles, as well as between agglomerated particles and matrix walls. The results of the statistical analysis showed significant differences between the tested materials in energy consumption during the pelletizing process.

A comparison of the results of the analysis of the energy consumption of the pelletizing process indicated that the values were lower than those reported by Garcia et al. [58]. In the cited study, the authors performed densification on a mixture of pine sawdust and waste obtained from the food and forestry industry in the form of coffee residues, cocoa shells, grape marc, and pinecone fragments, and the energy consumed for their pelletizing was in the range of 80–250 $Wh \cdot kg^{-1}$. In addition, Kirsten et al. [59] observed a higher energy demand (157–290 $Wh \cdot kg^{-1}$) for the hay compaction process, taking into account the grinding of waste into pieces of various sizes (2–6 mm). In the study on waste resulting from the pelletizing of corn cobs [40], the energy consumption was at the level of 80–400 $Wh \cdot kg^{-1}$. However, the authors emphasized that the process was not optimized, and the high values refer to the lower efficiency of the pelletizing process, which is related to the experiment they conducted. Zawiślak et al. [16] determined similar levels of energy consumption for the compaction of biomass in the form of chamomile and birch sawdust waste (108 and 100 Wh·kg^{-1}, respectively). The reason for this similarity could be the low humidity of these materials. However, for mixtures of these materials with pea and soya waste in various proportions, the energy consumption was lower by 38.4–44.7 Wh·kg^{-1}, which is due to the content of fats in the materials added. A relatively low level of energy consumption (10 Wh·kg^{-1}) was reported by Tan et al. [56] for the compaction of waste in the form of *C. oleifera* Abel. shell. In this case, the reduction of the compaction energy was due to the high content of lignocellulose in the raw material, as well as to the corresponding improvement of the plastic properties of lignocellulose by the proper hydration of the surface and the interior of the particles of the agglomerated material.

The energy density of the pellets obtained in this study ranged from 5.81 (CC-CH) to 8.19 GJ·m^{-3} (CC). The analysis of this parameter showed that the largest amount of energy was accumulated in the volume of pellets from CC, with average amounts in the pellets from CC-CG and CH-CC, and the lowest in the pellets from CC-CH. The differences in energy density between the pellets from CG, CG-CC, and CG-CH, as well as from CH-CG and CH-CC, were not statistically significant. Moreover, it was noted that, in the case of mixtures, the content of CC had an apparent effect on the energy density of the tested pellets. With regard to the results of other authors, it should be emphasized that different methods were adopted for determining energy density. The calculation carried out by Garcia et al. [59] corresponded to the methodology adopted in the present study. The authors obtained higher energy density values, in the range of 7.7–12.0 GJ·m^{-3}, which was due to the use of wood waste, in combination with waste from the agri-food industry, as raw material for pellet production. However, considering biomass combustion heat and pellet density for the calculation of lower heating values, as was performed by Jiang et al. [55] and Zhang T. et al. [11], for pellets obtained from corn drying process waste, the energy density was found to range from 14.8 (for CH) to 21.3 GJ·m^{-3} (for CG), and the values were intermediate for CC and all the mixtures. All pellets from the mixtures containing CG had a higher energy density, and the addition of CH contributed to the decrease in this parameter. A similar energy density in the range of 15.5–20.4 GJ·m^{-3} was obtained by Jiang et al. [55] for pellets made from a mixture of waste biomass and sewage sludge, and by Zhang T. et al. [11] for a mixture of wood waste from apple trees, corn straw, and frying oil.

Figure 3 shows the energy parameters of the obtained pellets in relation to the energy needed for their production from the tested raw materials.

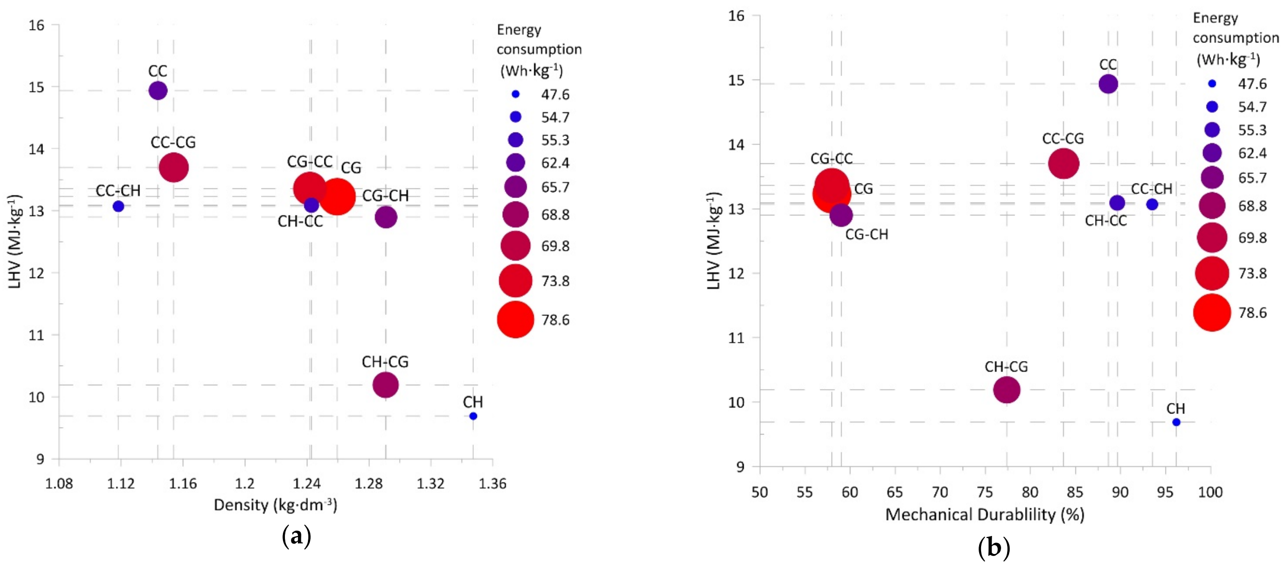
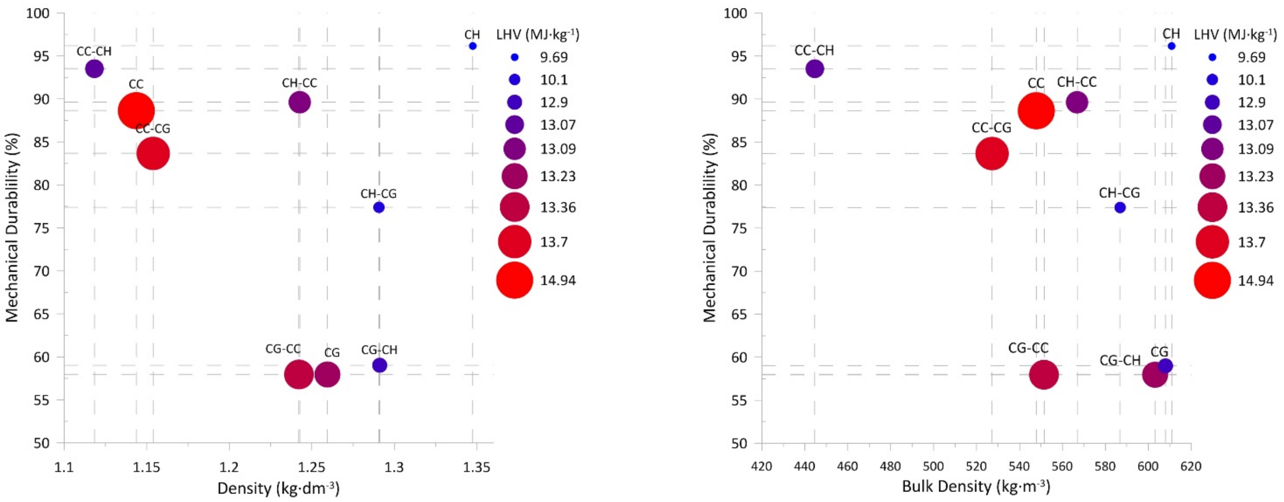


Figure 3. Quality parameters of pellets in terms of their properties as potential fuel: (**a**) for a single pellet; (**b**) for the total fuel.

The high density of pellets generally leads to, among other things, a reduction in the demand for storage volume, as well as a lower level of combustion chamber filling at a constant fuel weight. In this study, the pellets made from the CG-CH mixture, at the average lower heating value (12.90 MJ·kg^{-1}), showed a higher density (1.29 kg·dm^{-3}) and average energy consumption (65.7 Wh·kg^{-1}) compared to the other tested materials. This indicated that pellets produced from the mixture of corn grain and husks are a good-quality biofuel, and their production does not require a large amount of electricity. However, the low mechanical strength of these pellets (78%) can lead to their massive crushing, which, in turn, can trigger problems both in the fuel feeder and during the combustion process in the boiler burner. Considering the above, pellets made from the CH-CC mixture produced from the tested raw materials can be considered as a fuel with good quality parameters, with a satisfactory lower heating value (13.09 MJ·kg^{-1}) and low energy consumption in the manufacturing process (55.3 Wh·kg^{-1}), as well as a high density (1.24 kg·dm^{-3}) and high mechanical strength (89%). These features allow a positive energy balance for pellets made from the CH-CC mixture due to the positive ratio of lower heating value to energy consumption. Among the tested pellets, those made from CH showed the worst properties as a fuel due to their low lower heating value (9.69 MJ·kg^{-1}), despite the lowest energy input required for their production (47.6 Wh·kg^{-1}). The use of CC pellets as a biofuel is also advantageous due to their favorable lower heating value (14.94 MJ·kg^{-1}), as well as high mechanical strength (88.65%) and low energy consumption for pelletizing (62.4 Wh·kg^{-1}). Despite the low density of these pellets (1.14 kg·dm^{-3}), they can be a potentially attractive biofuel due to their other favorable characteristics.

Figure 4 shows the quality parameters of the obtained pellets in terms of the energy properties of the examined biomass.



(**a**) (**b**)

Figure 4. Quality parameters of pellets in terms of lower heating value: (**a**) with respect to the density (granules) of pellets; (**b**) with respect to the bulk density of fuel.

Analyzing the results of the study presented in Figure 5a, it was found that the pellets made of the CH-CC mixture were the most beneficial in terms of energy use. Their high mechanical strength (89.64%) and density (1.24 kg·dm^{-3}), together with the average lower heating value (13.09 MJ·kg^{-1}), indicated that they can be optimal biofuel. Additionally, the high bulk density of these pellets (566.9 kg·m^{-3}) and high lower heating value testify to their efficiency as a biofuel. Although favorable physical properties and a relatively high lower heating value were found for the pellets produced from CC-CH, CC, and CC-CG, these had the lowest density (<1.15 kg·dm^{-3}), which indicated their low susceptibility to compaction during pressure agglomeration. On the other hand, corn husk pellets showed very good physical properties, but a low lower heating value (9.69 MJ·kg^{-1}), and hence, were deemed unattractive. Similarly, due to their low mechanical strength, the pellets made from CG-CC, CG-CH, and CG, despite having a satisfactory lower heating value, were regarded as unattractive fuel, as these materials did not meet the quality criteria of the energy market, and they can only be used for the own needs of the pellet producers.

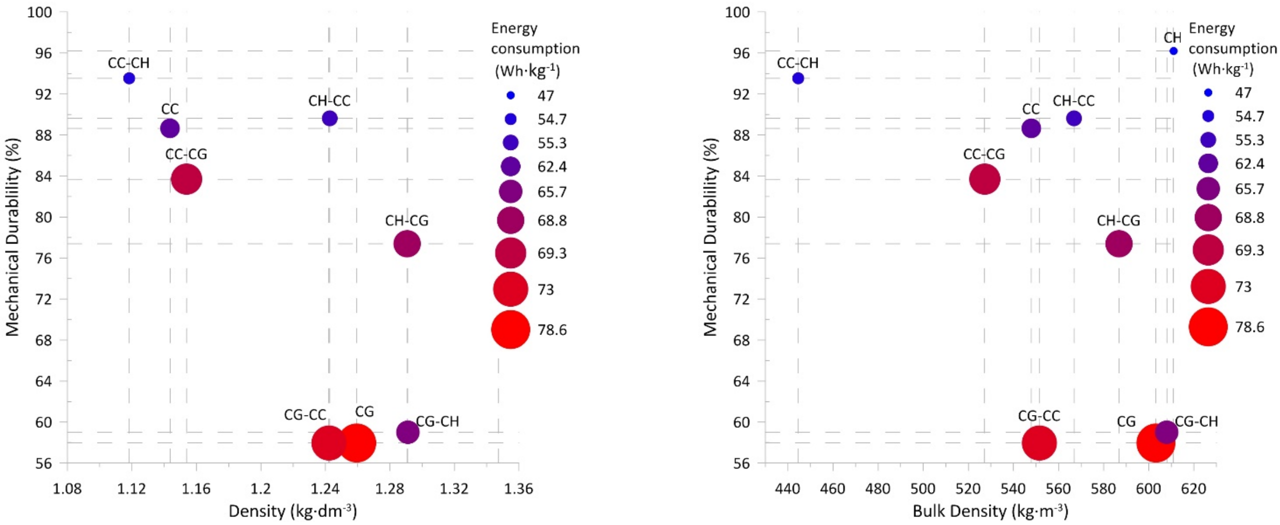


Figure 5. Quality parameters of pellets in terms of distribution and energy consumption of production: (**a**) with respect to the density (granules) of pellets; (**b**) with respect to the bulk density of fuel.

Figure 5 shows the quality parameters of the obtained pellets in terms of their properties related to storage and distribution processes.

The least advantageous, from the perspective of the logistics of pellet distribution to the recipient, were the pellets made from the CC-CH mixture. Despite the low energy input for their production (54.7 Wh·kg^{-1}) and the high mechanical strength of the resulting granules (93.52%), these pellets had a low bulk density (444.6 kg·m^{-3}). Therefore, the transportation of a certain mass of these pellets would require a larger loading and storage volume, which may be reflected in the profitability of distribution. However, the tested mixture could be used for local needs, such as in grain-drying plants. The most advantageous, from the perspective of the distribution logistics of biofuel on the energy market, were the pellets made from CH. The lowest energy input for the production of these pellets (47.6 Wh·kg^{-1}) would be reflected in profits from their sale. In addition, the high mechanical strength of these pellets (96.19%) would allow minimizing their crushing during transport, as well as during handling and storage. It is also worth noting that these pellets had the highest bulk density (610.9 kg·m^{-3}) among the ones tested. Such high bulk density would allow a large amount of pellets to be stored and transported in limited cargo space. In turn, the optimal quality parameters for the distribution process were found for the pellets made from CC and CH-CC. The low energy input required for the production of these pellets (62.4 and 55.3 Wh·kg^{-1}, respectively), as well as their satisfactory mechanical strength (88.65 and 89.64%, respectively) and average bulk density (547.9 and 566.9 kg·m^{-3}, respectively), pointed out that these materials are preferred for distribution and have good physical properties.

4. Conclusions

The findings of this study suggest that the use of waste resulting from the corn grain drying process in the form of pellets may allow obtaining granules with different quality characteristics. Taking into account the density (1.35 kg·dm^{-3}), mechanical strength (96.19%), and bulk density (610.9 kg·m^{-3}), the pellets made from CH were the most advantageous, while those made from CH-CG and CC-CG were beneficial in terms of pellet diameter (6.46 mm) and length (37 mm), respectively. The study proved that pellets produced from mixtures have low durability. During the production of pellets, it is important to ensure that the energy consumed for the granulation process is low, so that the process itself is energetically justified. The assessment of the tested pellets showed that the most energy-consuming material during pelletizing was CG (78.6 Wh·kg^{-1}), while CH was the least energy-consuming (47.6 Wh·kg^{-1}).

The study also proved that the fuel characterized by good quality parameters was the pellet made of the CH-CC mixture, with a satisfactory lower heating value (13.09 MJ·kg^{-1}) and low energy consumption in the manufacturing process (55.3 Wh·kg^{-1}). Moreover, data analysis revealed that the obtained pellets had a high density (1.24 kg·dm^{-3}) and high mechanical strength (89%), which are important for their distribution and handling.

Regarding the quality parameters for the distribution process, the pellets made of CC and CH-CC were found to be the most favorable, with a relatively low energy input required for their production (62.4 and 55.3 Wh·kg^{-1}, respectively) and high mechanical strength (88.65 and 89.64%, respectively). In addition, the bulk density of these pellets (547.9 and 566.9 kg·m^{-3}, respectively) confirmed their good physical properties, which are critical for efficient fuel distribution. However, the CC-CH mixture was identified as the least beneficial in terms of pellet distribution logistics. Although this material was characterized by a low energy input for pellet production (54.7 Wh·kg^{-1}), and the obtained pellets had a high mechanical strength (93.52%), the assessment showed that the pellets had a low bulk density (444.6 kg·m^{-3}). The results presented in this paper may form the basis of further works undertaken to optimize the compaction process for selected raw materials, in order to obtain pellets of the highest quality.

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Nomenclature

ED	energy density (Wh·kg^{-1})
EC	energy consumption (GJ·m^{-3})
DU	mechanical durability (%)
D	pellet density (kg·m^{-3})
BD	bulk density (kg·m^{-3})

LHV	lower heating value (MJ·kg^{-1})
Di	diameter of pellets (mm)
L	length of pellets (mm)
M	moisture content (%)
a, b, c, d	significant difference at the level of (α) of 0.05
S_x	standard deviation
α	significance level
CC	corn cobs
CC-CH	corn cob–corn husk mixture 4:1 *v*/*v*
CC-CG	corn cob–corn grain mixture 4:1 *v*/*v*
CG	corn grain
CG-CC	corn grain–corn cob mixture 4:1 *v*/*v*
CG-CH	corn grain–corn husk mixture 4:1 *v*/*v*
CH	corn husk
CH-CG	corn husk–corn grain mixture 4:1 *v*/*v*
CH-CC	corn husk–corn cob mixture 4:1 *v*/*v*

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