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Assessment of the Characteristics of Corncobs Used for Energy Needs

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Abstract: Due to environmental pollution and global warming, the use of renewable energy sources such as agricultural residues is gaining attention. Corn is the main source of food in many countries, and after harvesting it, the agricultural and industrial sectors generate significant amounts of residues. This study focused on corncob processing, its preparation, and the evaluation of its characteristics for energy needs. There was no significant difference between drying with active ventilation in the dryer and outdoor drying conditions. The adequate moisture content of corncob pellets is 12.39% at a compression ratio of 3.43 ± 0.011 and a maximum pellet density of 1012.96 ± 3.35 kg m^{-3}. The variation in pellet density at a given adequate moisture content is at least 0.78%. The compression ratio of the pellets compacted on the horizontal matrix granulator is 9.75% higher than that of the pellets produced on the laboratory automatic press. The corncob's lower calorific value was 17.35 ± 0.14 MJ kg^{-1}, and the ash content was 1.78 ± 0.24%. The produced pellets are strong enough and can be used for combustion. This research may help to better understand the properties of corncobs and their energy potential.

Keywords: corncob; drying; preparation; biofuel properties

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1. Introduction

As a clean energy source, biomass currently accounts for a significant proportion of global energy consumption, and its utilization is expected to increase in the future [1,2]. Alternatively, biomass can be used to produce fuels, electricity, and products that would otherwise be produced from fossil fuels [3,4]. Population growth, improved and intensified agricultural practices, and increased activities are leading to an increase in agricultural and food waste [5]. Growing concern over depleting fossil fuel resources [6] and the environmental impact of greenhouse gasses (GHGs), geopolitical instability and customer demands are some of the factors driving the utilization of biomass as a source of renewable energy [7].

The need for biofuels from environmentally friendly and cost-effective agricultural residues is more important than ever, and this has further accelerated the pace of the search for alternative resources [5]. One of the most effective strategies to reduce greenhouse gas (GHG) emissions and dependence on fossil fuels is to increase the use of renewable energy globally and to use biomass and waste as feedstocks for biofuels and bioproducts [4,8]. Agricultural residues have a high potential to replace fossil fuels and reduce greenhouse gas emissions in the energy production sector. Solid biomass is the largest source of biomass used for heat and power generation. The conversion of agricultural residues into biofuel has no negative impact on the food industry and contributes to waste management [5]. In addition, the utilization of agricultural waste as a thermal fuel for energy production will increase the profitability of the agricultural industry and increase the value of rich

low-value agricultural wastes [9]. Biomass comes from various sources, including energy crops, agricultural and forestry waste, and municipal and commercial waste. The main advantages of biomass among renewable energy sources are its nearly neutral carbon emissions and the availability of multiple sources of supply [3].

To reduce the low bulk density, various densification processes have been used, mainly through physical–mechanical procedures [7,10]. The densification process converts the raw material into a homogeneous, high-quality product with advanced physical and mechanical properties, lower moisture content, and higher energy density [11]. Popular biomass densification systems include briquetting and pelletizing due to the high energy content per unit volume [12,13]. Pelletizing and briquetting technologies present similar process steps but differ in terms of the equipment used to compress the material; the type, size, and shape of the raw material to be compacted; and the treatment of the raw material before the pelletizing and briquetting processes [4,11,13]. Trubetskaya et al. [4] carried out the torrefaction of wood chips, and olive stones before briquetting. The pelletizing process also includes a pellet cooling step, which affects the mechanical properties of the pellets by providing strength and hardness. In addition, this stage removes dust (a by-product) [11], which can cause spontaneous combustion. The pellets also offer better opportunities for smaller boilers and automation. It is known that some parameters affect the quality and properties of the final product, including but not limited to the particle size of the raw material, the initial moisture content, and the chemical composition [14]. Before compaction, the raw material is dried. The drying process is required for both pelletizing and briquetting systems to obtain a more finely processed feedstock, depending on the moisture content. This parameter is one of the most important variables affecting the binding mechanisms and therefore the quality of the product [11,13].

Corn is the second most popular and widely grown agricultural crop in the world [3]. In the USA, 40% of the corn harvest is used in the food and feed industry, 39% in ethanol production, and 13% for export [6]. The global average corn production between 2013 and 2021 was 1 billion tons [15]. With a kernel share of approximately 70%, pith share of 22%, and leaf share of approximately 8% of the total cob weight, the use of corn pith as biomass is not harmful to the food and feed industry [16]. For every weight of corn crop, corn stover waste accounts for 50% of the weight [17], whereas the cob accounts for 75–85% of the corn ear weight [18]. After harvesting corn grain, the remaining leaves, stalks, and cobs are usually left on the field for soil improvement [19]. Corn production generates a large amount of waste from the agricultural industry [19,20]. Rarely are the residues from this crop fed to livestock [21]. In many countries, corncob is an agricultural crop residue that has been burned off directly for electricity or wasted as biomass [21,22].

It is known that in order to utilize corncob feedstock as a biofuel, it is first necessary to determine the biofuel preparation and the main property parameters. When biomass is prepared into pellets for energy use, it requires proper treatment, i.e., drying before milling, because the moisture content of the raw material is reduced after milling, and the compaction requires the appropriate moisture content of the raw material. These operations are required to ensure that the uncompacted raw material is easy and inexpensive to store and transport. The use of agricultural residues as fuel in their original form is difficult because of their irregular shape, low bulk density (<150 kg m^{-3}), and high transportation and storage costs [9,23]. Oladeji and Enweremadu [24] also confirm that corncob tends to be low in bulk density, with a moisture content of up to 45% when it is harvested from the farm when partially dried. Therefore, to overcome these problems, the densification of biomass into pellets was considered. The results reported in the literature show that maize cobs have poor physical properties, high moisture content, and low calorific value [16].

Even though it is not as energy-intensive as fossil fuels, corncobs have an energy density similar to other biomass fuels. Another advantage of corncobs is that they produce a higher bulk energy content. However, the literature review by Kaliyan and Morey [25] indicates that high-density and -durability compacted corncob products are best suited for use with (0.5–1.0 mm particle diameter) feedstock with a moisture content of 8–20%.

Research by Muazu and Stegemann [26] highlights the need to add starch and water to ensure sufficient strength of corncob briquettes. The results of Aransiola et al. [27] showed that the moisture content of the compacted corncob ranged from 4.43 to 7.62% (db), the loosening densities of the produced briquettes ranged from 729 to 987 kg m^{-3}, and the compressive strengths ranged from 1.02 to 8.32 MPa. Many other researchers have reported that the densification properties are highly dependent on moisture content, milling size, temperature, densification pressure, and type of raw material [28–30]. Therefore, a very important factor when choosing raw materials for pellet production is to consider the moisture content of the raw materials. It is noted that there is still no consensus on the adequate moisture content of the raw material required for corncob densification.

A review of existing studies shows that there is an acute lack of comprehensive information on the preparation of corncobs for densification and their biometric parameters, and there is still great uncertainty in estimating the moisture content of the raw material before densification. Therefore, the main focus of this study is on the production of pellets from corncobs: evaluating the characteristics of the corncob drying process; the effect of drying on the parameters of the chemical composition; milling efficiency in evaluating fraction composition; compaction capabilities and resistance to compression; determining the most adequate moisture parameters in the raw material; verifying the efficiency of adequate moisture compaction of the raw material in the pellet production process; and determining their biometric properties, mechanical durability, calorific value parameters, and ash content. The aim of our research is, therefore, to evaluate the preparation of corncob and the physical–mechanical parameters of the compacted raw material by determining the moisture content of the adequate raw material for pellet densification and to verify the efficiency of compaction of the raw material at the adequate moisture content in the process of pellet production, by determining its biometric properties, mechanical durability, calorific value parameters, and ash content. It is hoped that this research will be useful for the future use of corncob as an alternative energy source. Knowing the nuances of the preparation and the adequate moisture content of the feedstock during densification, as well as further research, can lead to improvements in biofuel preparation technologies, increasing efficiency and reducing production costs and environmental impact.

2. Materials and Methods

2.1. The Raw Material and Experimental Design

The maize species was *Pioneer P8000*. This research was conducted in the laboratory of the Department of Mechanical, Energy, and Biotechnology Engineering, Faculty of Engineering, Vytautas Magnus University Agriculture Academy.

Figure 1 shows the plan of experimental research, indicating the technological operations of the raw material preparation and the research being carried out.

In order to achieve the objectives of the study, the research will follow the following sequence:

1. Firstly, the production of pellets from corncob raw material is experimentally investigated under laboratory conditions. This stage involves
    - A detailed assessment of the dynamics of the pellet production process, examining the characterization of the drying process and its influence on moisture changes, bulk density, and chemical composition parameters.
    - The crushing efficiency is assessed by evaluating the raw material fractional composition, bulk density, and moisture content.
    - Calculation of the amount of water to be used for wetting the raw material and determination of the parameters of the wetted raw material.
    - To determine the adequate moisture content of the raw material for an efficient compaction process, the compaction potential is evaluated by determining the compaction efficiency coefficient, the time dependence of the density, and the compressive strength of the pellets.

2. In the next step, the compaction efficiency of the adequate moisture content raw material in the pellet manufacturing process is verified. This process includes
   - The influence of the adequate moisture content of the raw material on the formation and retention of the pellet properties.
   - Evaluation of the biometric properties of the pellets.
   - Mechanical durability, calorific value parameters, and ash content are determined to give a complete picture of the quality and suitability of the resulting pellets for energy applications.

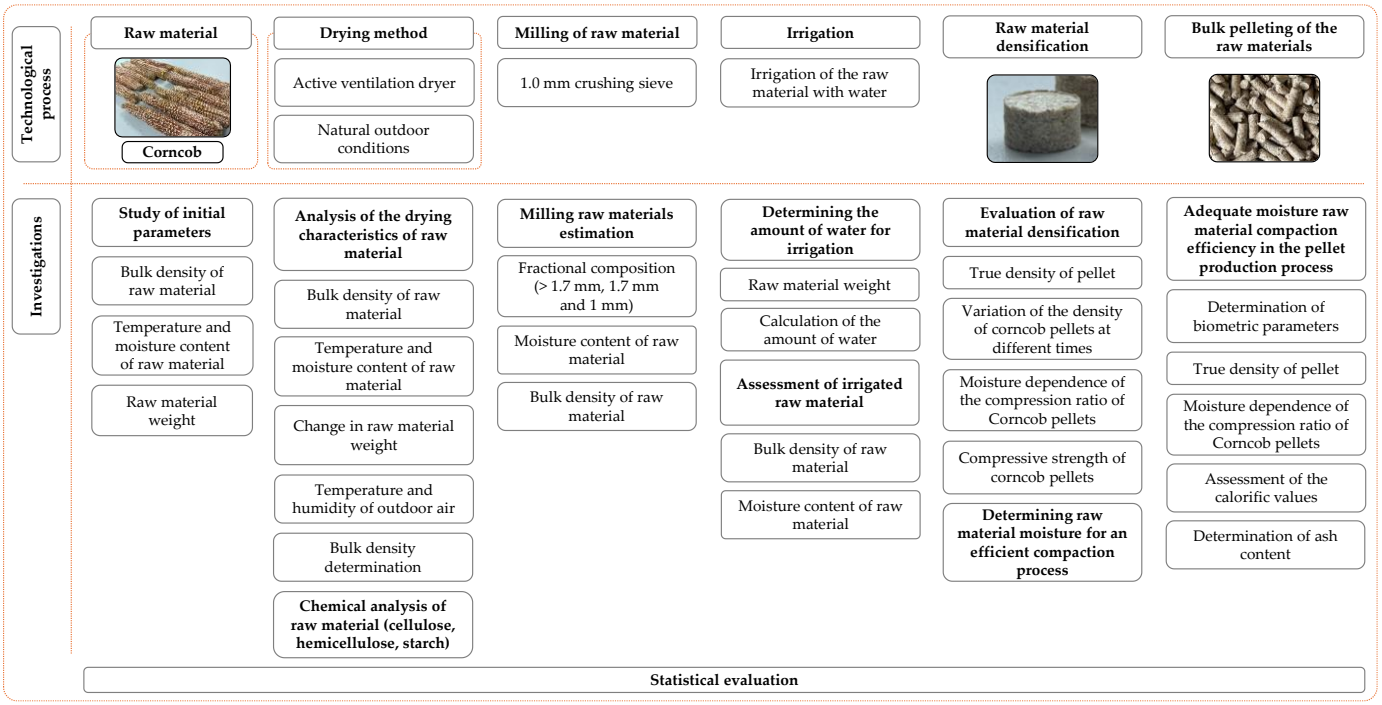


Figure 1. Visualization of the experimental research plan.

2.2. Investigation of Raw Material Drying Characteristics

The quantity available for corncob is separated into two parts for different drying conditions. The drying experiment was carried out in parallel in two ways: active ventilation (Figure 2) and drying in natural outdoor conditions, protected from precipitation (Figure 3).

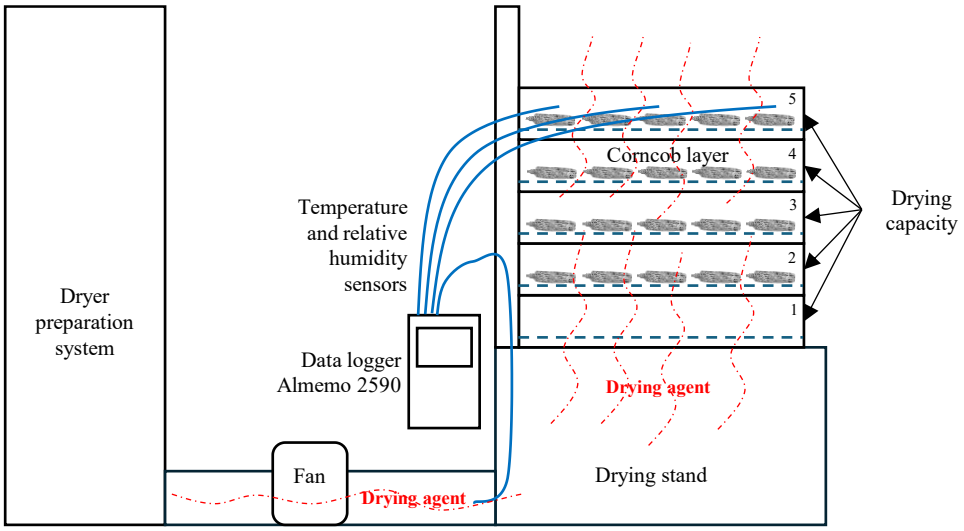


Figure 2. Principal scheme for drying corncobs on an active ventilation stand.

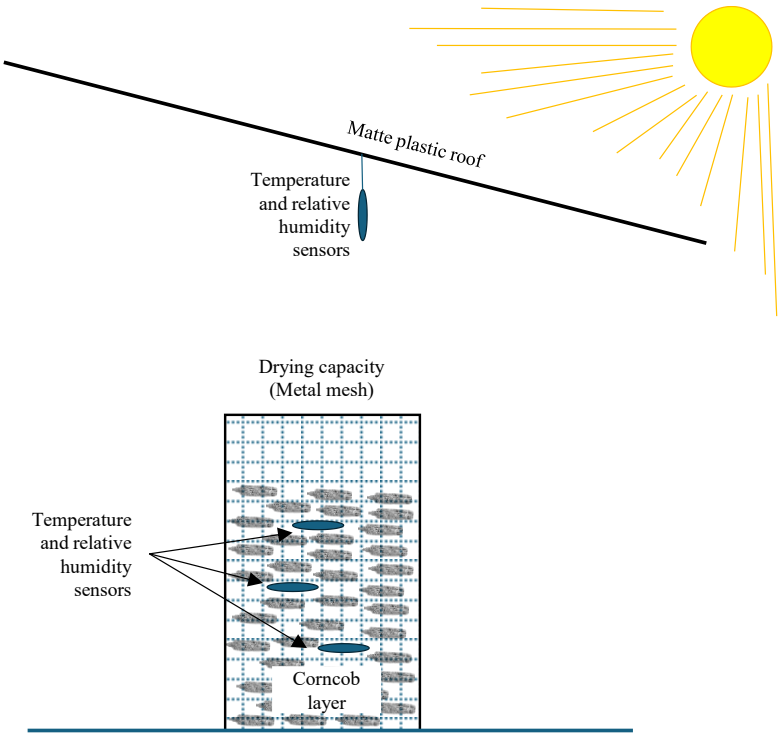


Figure 3. Principal scheme for drying of corncobs in natural outdoor conditions.

Active ventilation drying includes a special drying system, which prepares a drying agent at the required temperature and humidity in a drying stand (Figure 2). The drying system consists of an air flow conditioning system and a conditioning air reservoir, i.e., a collector. The conditioned air flow is fed by a fan into the drying stand. At the bottom of the drying stand, there is a layer of tiny stones to distribute the drying agent evenly throughout the drying area. The drying area consists of 5 wooden boxes with a mesh bottom (plastic mesh 2 mm × 2 mm) in which the corncob is spread in a single layer. The size of the wooden boxes is 850 mm × 766 mm × 92 mm (internal dimensions). The drying parameters (temperature and humidity) were measured with temperature and humidity sensors Almemo Normal FH A64S-21 (Ahlborn Almemo, Holzkirchen, Germany) at the dryer input and in the corncob layer. Drying parameters were recorded every 10 min and stored in an Almemo 2590 data logger (Ahlborn Almemo, Holzkirchen, Germany).

Drying intensity was measured at intervals of 2 days using a Schiltknecht Swiss precision air flow wing anemometer S50059 (20 m s^{-1}) (Hitma, Uithoom, The Netherlands). An anemometer was used to measure the speed of the dryer through the corncob layers. The measured results were converted into a comparative dryer air flow model [31]:

$$L_{comp} = \frac{3600 \cdot F \cdot v}{M}, \quad (1)$$

where L_{comp} is the comparative dryer air flow rate, m^3 $(kg\ h)^{-1}$; F is the cross-sectional area of the ventilated box, m^2; v is the average air velocity through the corncob layer, m s^{-1}; and M is the mass of corncob in the drying tank, kg.

For natural drying, the stand was specially prepared for outdoor conditions and protected from precipitation by a frosted plastic roof (Figure 3). A cylindrical stand was made from a metal grid (14 mm × 8 mm). The stand has a diameter of 420 mm and a height of 1000 mm. Temperature and humidity were measured under the roof and in the loosely packed corncob layer. Wireless MicroLite USB data logger temperature and humidity sensors (MicroLite USB data loggers/Fourtec—Fourier Technologies, Rosh HaAyin, Israel) were used to monitor temperature and humidity. Drying parameters were recorded every 10 min.

In both conditions, corncob weight changes were monitored by periodic daily weighing (Sartorius Miras 2 scale (Sartorius Engineering Group, Göttingen, Germany)). The weighing results were converted into the moisture content of corncob:

$$w_i = 100 - \left(\frac{100 \cdot m - w \cdot m}{m_i} \right), \quad (2)$$

where w_i is the moisture content of corncob at the time of drying, %; m_i is the mass of dried corncob at the time of drying, kg; w is the moisture content of corncob at the start of drying, %; m is the mass of dried corncob sample at the start of drying, kg. The corncob was dried until the moisture content of the dried corncob in the drying tanks decreased to 15–20%. The drying time was approximately 300 h.

During further analyses, the chemical properties of the corncob, grinding efficiency, pellet bulking efficiency, and physical–mechanical and thermal properties of the pellets were evaluated to determine the suitability of the studied biomass for biofuel.

2.3. Determining the Moisture Content of Corncob

The moisture content of Corncob was determined in accordance with LST EN 14774-3:2010/P:2013 [32] by drying specially prepared samples to constant weight in an SFP 600 oven (Memmert GmbH, Schwabach, Germany) at 105.0 ± 2.0 °C. The moisture content was determined at the following stages: pre-drying, post-drying, fractional crushing, and pelleting. The amount of moisture in the material was determined after 6 repetitions.

2.4. Chemical Analysis of Corncob

Determination of cellulose and hemicellulose content and determination of starch content by the spectrophotometric method using enzymatic hydrolysis of corncobs were performed in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry. The tests were repeated 3 times, before and after drying in both cases.

2.5. Corncob Milling and Its Assessment

Corncobs were crushed using a RETSCH SM 300 (RETSCH GmbH, Haan, Germany) chopping mill at 2000 rpm min^{-1} and a 1.0 mm crushing sieve, followed by a RETSCH ZM200 crushing mill (RETSCH GmbH, Haan, Germany) at a variable speed of 8000 rpm min^{-1}. To determine the crushing efficiency, the crushed mass was separated into fractions. The fractional composition of the crushed mass was determined using an electric shaker Haver EML Digital Plus (Haver & Boecker, Oelde, Germany) with a sieving mode of 3 min, an interval of 20 s, and an amplitude of 2 mm, and a set of sieves with a hole diameter of 1.0 mm and 1.7 mm (RETSCH GmbH, Haan, Germany). A total of three fraction sizes (>1.7 mm, 1.7 mm, and 1 mm) were obtained. No sieves with larger holes were needed because raw material passed through the above sieves. After sieving, the raw material remaining on the sieve was weighed (Sartorius AX6202, Max 6200 g, d = 0.01 g). Five repetitions of the study were performed.

2.6. Density Determination

The density of the dried raw material of the corncob, the density of the milled raw material, and the bulk density of the densified pellets were determined.

The bulk density was determined according to the methodology of Jackson et al. [33]. For the determination of the bulk density of the raw material, a cylindrical device of a known volume (volume 2.3 l and mass 549.2 g) consisting of measuring and filling cylinders, a valve, and a piston is used. The measuring and filling cylinders are connected by a piston and a valve.

The filling cylinder is filled with raw material, the flapper is pulled tight, and the piston with the contained raw material is dropped into the measuring tank. The tanks are separated, and the material over the ground raw material is carefully scraped from the top of the measuring tank. The measuring tank and the raw material were then weighed with

a KERN KVB-TM (Kern & Sohn GmbH, Albstadt, Germany). The results were converted to the bulk density of the material. Analyses were performed in 5 repetitions.

The density of the pellets was determined by measuring the dimensions of the densified pellets. Analyses were performed in 5–12 repetitions.

2.7. Irrigation of Corncob Milled Biomass

Determining the primary moisture content of the milled corncob biomass determines the amount of water that is needed to moisten it to the required moisture content. The milled corncob mass was moistened by spraying with water and left for 24 h with periodic stirring. The water required for moisture is calculated as follows [34]:

$$m_{H_2O} = \left[\frac{m_0(100 - w_0)}{(100 - w_d)}\right] - m_0, \quad (3)$$

where m_{H_2O} is the amount of water required to moisture the milled corncob to the required moisture content, kg; m_0 is the starting quantity of milled corncob, kg; w_0 is the starting moisture content of milled corncob, and %; w_d is the required moisture content of the milled corncob to be moistened, %.

2.8. Corncob Densification and Its Evaluation

After the preparation of the milled 1 mm raw material and moistening to the required moisture content, the density process was applied. The raw material was pressed using an automatic benchtop laboratory ATLAS Autotouch 40T press (Specac Ltd., Orpington, UK). To produce pellets, samples of milled raw material weighing approximately 4 g were transferred into a pressing matrix (diameter 20 mm), which was placed in the press and subjected to a pressing force of 780 MPa (245 kN). The holding time was 15 s. After pressing, the pellet was rapidly removed, and its primary dimensions (height and cross-section) were determined. Measurements were taken immediately after pressing and after 10 min, 1 h, 2 h, 3 h, and 2 days (ambient temperature—16.2 ± 1.1 °C, relative humidity—41.2 ± 2.4%). An electric BMI caliper (0–150 mm) with an accuracy of ±0.01 mm was used. The pellets were evaluated by measuring their height and diameter.

The analysis of the densification process will assess the quality of pellet compression by calculating the compression ratio. This indicator shows how pressing the same mass changes the bulk density:

$$\lambda = \frac{\rho_p}{\rho_b}, \quad (4)$$

where λ is the densification factor; ρ_b is the bulk density of the milled raw material before pressing, kg m^{-3}; and ρ_p is the actual density of the pellet, kg m^{-3}. The higher the λ, the more efficient the densification process; i.e., the pellets become denser, or the bulk density is reduced.

2.9. Analysis of the Compressive Strength of the Pellets

The compressive strength of the pellets was tested using an INSTRON 5965 (ITW, Glenview, IL, USA) 5 kN capacity testing machine with static loading speeds of 20 mm·min^{-1} and limited movement. The obtained results were processed using Instron Bluehill® software (version 3.11.1209). The tests were based on fuel pellets placed on a horizontal plane and subjected to a vertical load. The test had to be repeated 5 times. For each test, pellets that complied with the moisture content, diameter (mm), and length (mm) specified in the standards were selected. The results were recorded every 0.1 s until the pellet failed. The measurement tolerance was 0.02%.

2.10. Bulk Pelleting of the Raw Materials

The remaining milled raw material (size 1 mm) was moistened to the previously determined moisture content adequate raw material moisture and compacted into pellets of 6 mm in diameter. A small capacity granulator with a horizontal matrix was used for

mass densification of the pellets. After the pellets were cooled, their biometric parameters such as dimensions, moisture content, volume, and density were estimated.

Assessment of the durability of the pellets prepared. Evaluation of the brittleness of the corncob pellets was carried out according to the Lithuanian standard LST EN ISO 17831-1:2016 "Solid biofuels. Determination of the mechanical durability of pellets and briquettes. Part 1: Pellets" [35]. To determine the fractional composition of the pellets before the mechanical durability test, a quantity of 1 kg of pellets was produced and inserted into a Haver EML Digital Plus electric shaker. The sieving mode of the electric shaker was set to 3 min, with an interval of 20 s and an amplitude of 2 mm. The set of sieves to be used consisted of sizes 1.0, 1.7, 2.5, 3.15, 4.5, and 6.5 mm. After sieving, the raw material remaining on the sieves was weighed (Sartorius scale AX6202, Max 6200 g, d = 0.01 g). To determine the fractional composition of the raw material after the mechanical strength test, the individual fractions of the sample were mixed and poured into the DELTA pellet and briquette strength stand. The stand was set at 50 rpm for a 5 min operating range. The pellets were deformed by the forces of gravity and abrasion. At the end of the test, the pellets were removed from the stand and placed back into the Haver EML Digital Plus electric shaker. After the sieving was completed, the raw material remaining on the sieves was weighed. A fraction smaller than 3.15 mm was taken for evaluation, in accordance with the requirements of the standard. Five repetitions were performed.

2.11. Assessment of the Calorific Values

The calorific values of the material (initial milled corncob biomass; pellets with a size fraction > 3.15 mm; and pellets with a size fraction < 3.15 mm) were measured according to LST EN 14918 [36] and tested with an IKA C2000 Calorimeter Basic V1 230 V (Cole-Parameter, Bunker Court, Vernon Hills, IL, USA). Fine raw material samples are compacted with a hand press before being placed in the calorimeter. To determine the calorific values, the experiment was repeated 16 times.

2.12. Determination of Ash Content

Ash content analysis was performed in accordance with LST EN 14775 [37] using a Nabertherm P300 furnace (Ceramiktherm S.C., Lobez, Poland). The 1 g samples were heated to 250 °C for 1 h, and then the temperature was raised to 550 °C for 2 h. Ash content was measured as the mass loss of the samples after heating, and 16 repetitions were performed to determine ash content.

2.13. Statistical Evaluation

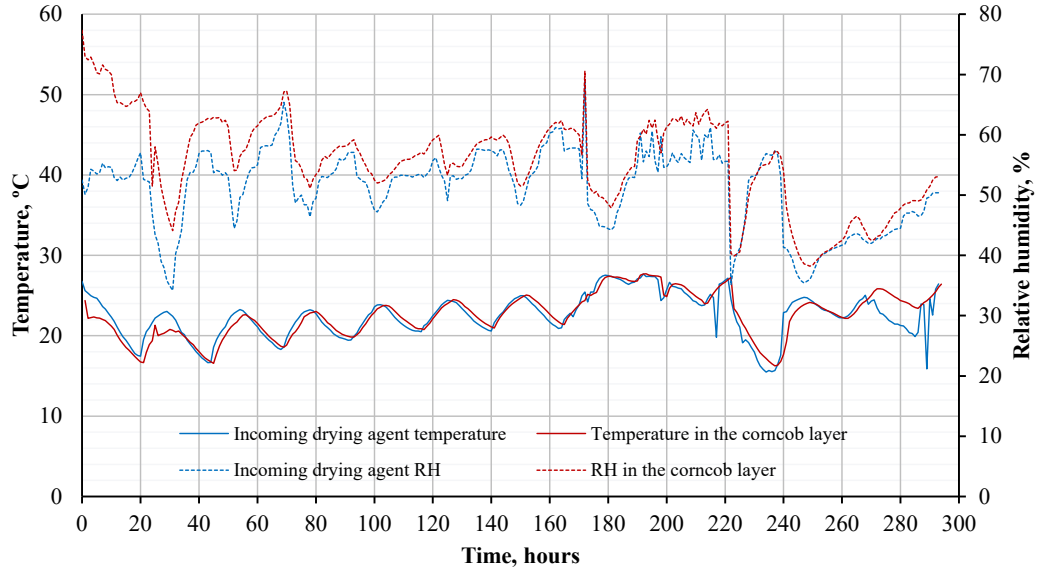
The data were evaluated using the statistical analysis software IBM SPSS 20 Statistics (version number 20.0, IBM, Chicago, IL, USA). The drying experiments were conducted in triplicate, and the data presented are expressed as an average value. Differences in chemical analysis between drying treatments were assessed by one-factor analysis of variance ANOVA with the Tukey HSD test. Differences before and after drying were considered significant at $p < 0.05$. In the following results, the independent variable (moisture content) showed a significant effect on chopped raw material, density, pellet density, compression ratio, and compressive strength and was compared by ANOVA with the Tukey HSD test with 95% confidence. It was also used to evaluate the significant difference between the group means of the milled raw material and the pellet fractions (two and a few, respectively) and assess these essential differences between different moisture groups of raw materials, determining the most adequate raw material moisture for pellet compaction. The level of significance between the data obtained was set at a p-value of 0.05.

The graphs were produced using Microsoft Excel software (Version 2404), and the data are summarized as means ± standard deviations.

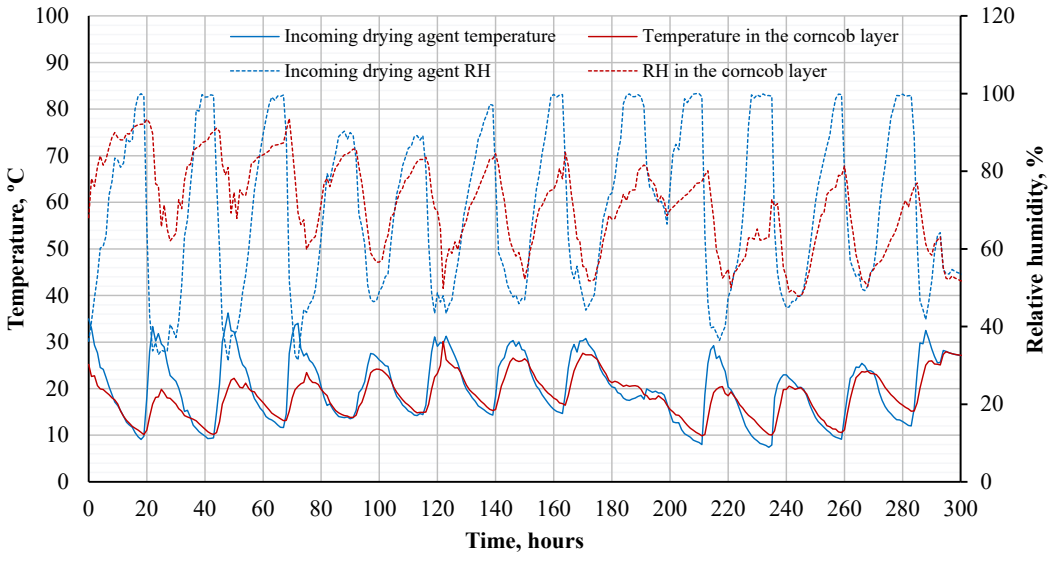
3. Results

3.1. Analysis of the Corncob Drying Characteristics

The main objective of this study was to determine the drying dynamics of corncob under different drying conditions, i.e., drying in active ventilation (Figure 4A) and drying in outdoor conditions (Figure 4B). The average daily drying parameters were not the same as expected in the active ventilation drying but showed a lower temperature variation than in the outdoor drying because the drying process was conducted using outdoor air, and the air prepared inside the conditioning system was provided to the drying box. The average temperature variation of the prepared drying agent supplied during the drying period ranged from 15.48 to 27.70 °C (RH—34.20–69.10%). The average comparative air flow rate of the dryer was about 3560 $m^3 \cdot (t \cdot h)^{-1}$. The outdoor weather had average temperature variations of 7.39–36.23 °C (RH—47.77–93.57%) throughout the drying period.

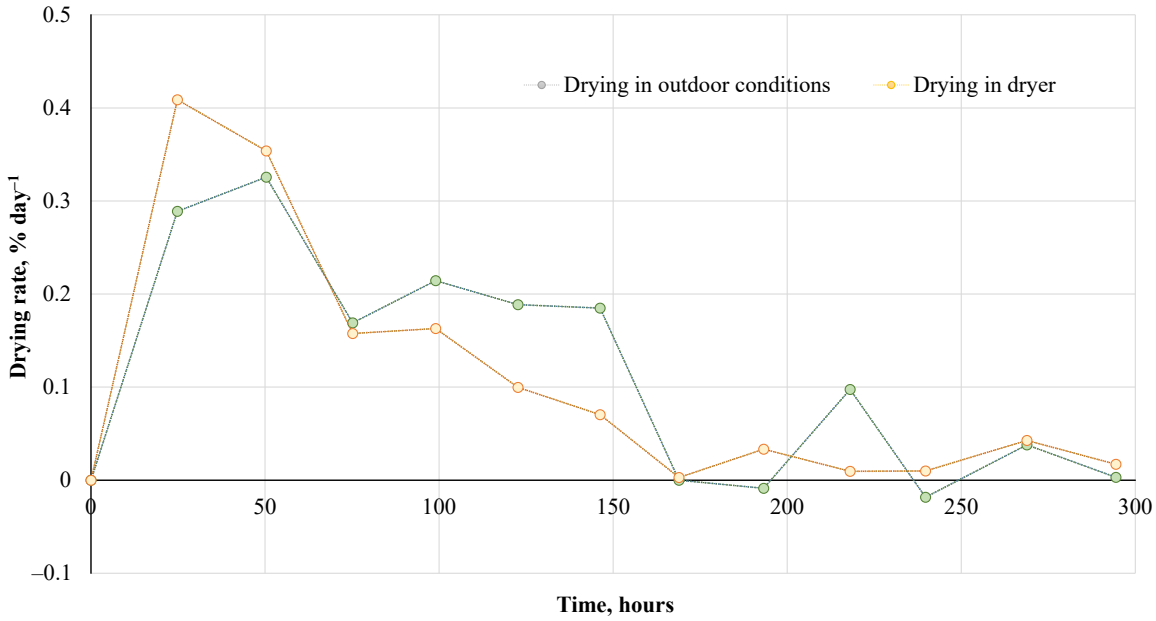


(**A**)

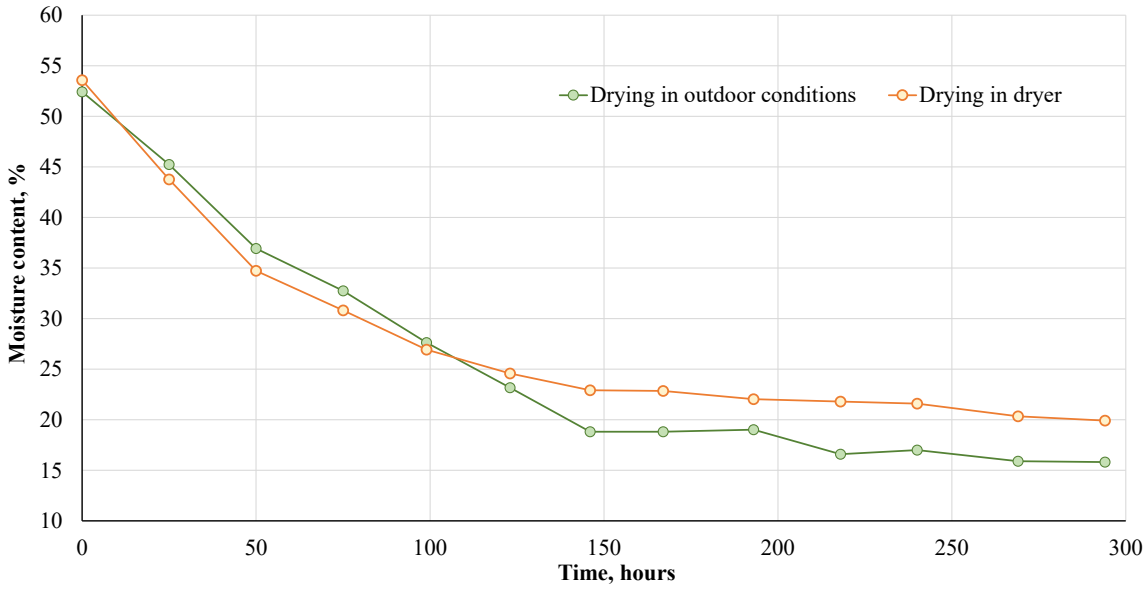


(**B**)

Figure 4. *Cont.*



(**C**)



(**D**)

Figure 4. Corncob drying characteristics: (**A**) drying in active ventilation; (**B**) drying in outdoor conditions; (**C**) dependence of raw material drying rate on drying time in an active ventilation dryer and outdoor conditions; (**D**) dependence of raw material moisture content on drying time in active ventilation and outdoor conditions. Results are presented as mean value (n = 3).

The difference between these parameters is quite significant, as the temperature dropped as low as 7.39 °C during the night period, while during the day it reached up to 36.23 °C in the sun. The variation in humidity in outdoor conditions was also significantly higher, especially during night periods and on rainy days (150–250 h). In the produce layer, the temperature variation was slightly lower in both drying periods—16.25–27.70 °C (RH—38.20–69.10%) in the drying active ventilation and 9.88–30.11 °C (RH—47.77–93.57%) in the outdoor conditions. In all cases, the differences were influenced by the outdoor air parameters.

Figure 4C,D show the changes in the moisture content and drying rate of the corncob material for both drying conditions. The initial mean moisture content of the corncob in the active ventilation dryer was 53.58 ± 3.34%, and in the outdoor conditions—52.42 ± 3.55% (n = 24). The drying rate (Figure 4C) during the first day in the dryer was the highest at 0.41% per day, which was about 29.3% higher than the outdoor drying rate (0.29% per day). After the first day in the active ventilation dryer, the drying rate of corncob decreased more continuously than in the outdoor conditions. In outdoor conditions, the maximum drying rate of corncob was reached on the second day (0.35% per day). The drying rate remained similar at around 0.17–0.21% day^{-1} for days 3 to 6.

Looking at the change in moisture content during the drying process under both conditions, it can be observed that the relative moisture content of corncob decreased steadily (Figure 4D). Although a higher drying rate was observed in the dryer, at the end of the drying process, i.e., on day 12, the final average moisture content of the corncob in the outdoor conditions was about 15.8%, which was about 20.5% lower than the average relative moisture content of the corncob dried in the active ventilation conditions (19.9%). It was observed that the corncob dried in outdoor conditions showed a negative drying rate on the 8th and 10th days of drying (−0.009 and −0.009, according to the −0.018% per day) as a result of rainy weather. However, in this case, the high humidity did not significantly affect the final (at the end of drying) moisture content of the corncob raw material, and the drying rate increased again during the day. In addition, the higher prevailing temperature during the day (up to 36.23 °C) influenced the decrease in the moisture content of corncob raw material at the end of drying.

As a result, the moisture content of the corncob material increased to 19% (approx. 1.1%). The peak drying rate on day 9 in outdoor conditions showed that the increase in air temperature led to a decrease in humidity of about 12.7% (to 16.6%) due to the higher outdoor temperature. On day 10, corncob moisture content increased again (about 2.33%). Studies have shown that, even in more moist times of the day (overnight or in the event of rain), the moisture content of the raw material can increase, while in the next half of the day, in warmer weather, this change can level off or decrease. In general context, the material dried in outdoor conditions during the same period was approximately 20.5% drier than in an active ventilation dryer. Corncob dried outdoors had a relative humidity of 18.8% on the 6th day, and it was 19.9% for corncob dried in the dryer. This means that the material dried in outdoor conditions dried in half the time. Of course, it also depends on the weather. It is possible that if there are more rainy days, drying could take longer or even not take place.

The evaluation of the change in the moisture content of corncob (Figure 4D) showed a consistent decrease in the moisture content of the material over 12 days. The experiment showed that the moisture content of the material depended on the drying conditions and the ambient temperature.

The dried corncob bulk density was 144.81 ± 8.05 kg m^{-3} for both drying conditions. The bulk density of corncob at the beginning of the drying process was approximately 128.64 kg m^{-3}, compared to a bulk density at the end of the drying process of approximately 153.74 kg m^{-3}. An increase of 16.33% in the bulk density of corncobs was obtained from the drying method.

3.2. Chemical Analysis of Corncob

Chemical analysis determined the percentage of dry matter of starch, cellulose, and hemicellulose in corncob before and after drying. The amount of these substances could affect the binding of the pellets during compaction. The results of the analysis are presented in Figure 5. First, the primary corncob contents were found to be about 6.89 ± 0.16% dry matter for starch, 34.89 ± 0.25% dry matter for cellulose, and 34.04 ± 0.17% dry matter for hemicellulose (n = 3).

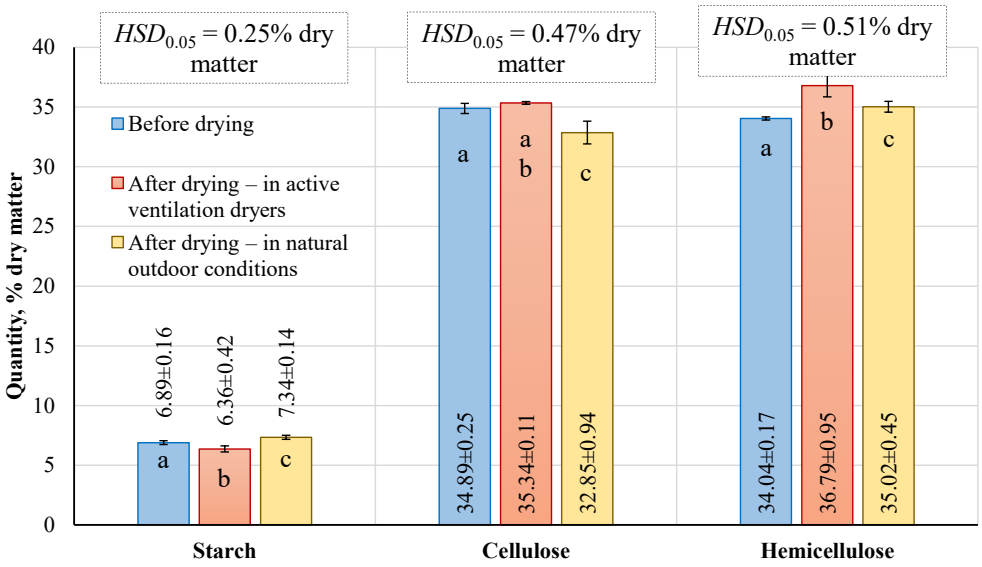


Figure 5. Starch, cellulose, and hemicellulose values in corncob before and after drying. Different lower-case letters indicate significant results at $p < 0.05$ based on one-way ANOVA with the Tukey HSD test ($n = 3$). The data are summarized as means ± standard deviations.

In the evaluation of the results of the study, Figure 5 shows the differences in the starch, cellulose, and hemicellulose contents of corncob between the different drying treatments, i.e., before and after both drying treatments (significant at the $p < 0.05$ level, based on a one-factor ANOVA with the Tukey HSD test). After drying by active ventilation, the starch, cellulose, and hemicellulose contents of corncob were 6.36 ± 0.42, 35.34 ± 0.11, and 36.79 ± 0.95% dry matter, respectively. Comparing the two treatments after drying, it can be noticed that the starch content decreased by 7.6% after drying in active ventilation but was 13.3% higher in the natural condition than in the active ventilation. There was no significant difference in cellulose content (35.34 ± 0.11% dry matter) between the original and post-activated drying conditions, whereas all other data were significantly different ($n = 3$, $p < 0.05$). In outdoor-dried corncob, 32.85 ± 0.94% dry matter was found, which was 5.8% less than that in the raw material. After drying in active ventilation, the hemicellulose content of the corncob increased by 7.5% (36.79 ± 0.95% dry matter), while after drying in outdoor conditions, this content increased by 2.8% (35.02 ± 0.45% dry matter). The difference between the treatments was 4.5%. It can be assumed that the cellulose and the hemicellulose content after drying corncob in natural conditions were lower than those after drying in active ventilation, which may have been influenced by different treatment conditions.

3.3. Corncob Milling and Evaluation

Milled corncob biomass was used to determine the corncob fraction. Figure 6 shows the fraction size, moisture content, and bulk density of the different fractions of the milled biomass in different drying conditions.

The 1.0 mm fraction size was the highest in outdoor drying at 71.63 ± 6.13%, and it was 66.27 ± 4.49% in the active ventilation dryer. Comparison between the moisture content of the different drying methods showed similar results, with the moisture content of the crushed 1.0 mm fraction drying in the dryer at 5.99 ± 0.03%, and in the outdoor conditions at 5.97 ± 0.05%. The results show that the dust content (<1 mm) was 26.07 ± 6.24 and 31.17 ± 4.54%, the fraction of 1.7 mm was 2.37 ± 0.21 and 2.57 ± 0.28%, and the bulk of the biomass (1.0 mm) was 71.63 ± 6.13 and 66.27 ± 4.49%. One-way ANOVA with the Tukey HSD test ($p < 0.05$, $n = 6$) showed that there was no significant difference in the amounts of fractions of corncob dried by different methods.

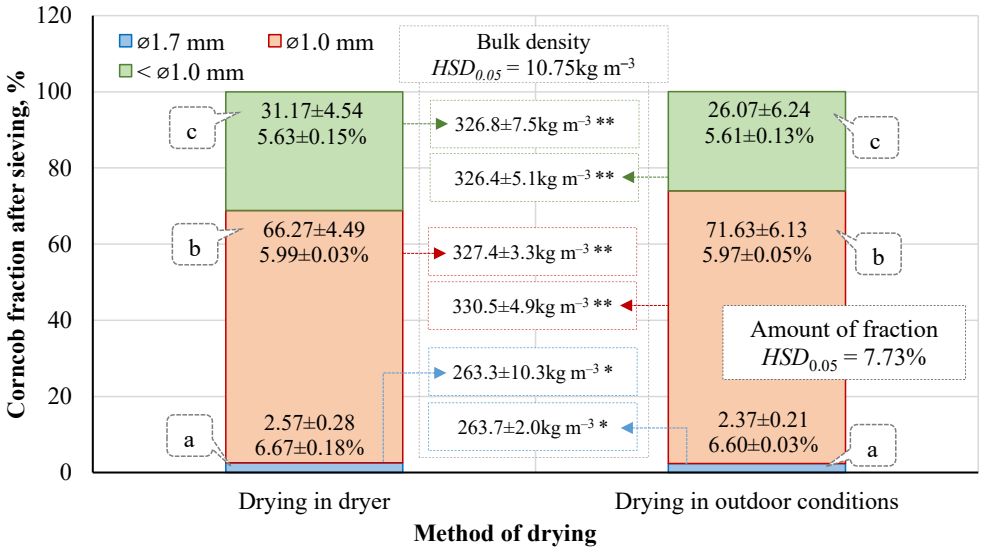


Figure 6. Fractional composition of corncob biomass. Results are significant at the $p < 0.05$ level, based on one-way ANOVA with the Tukey HSD test for differences between groups (fractions in lowercase letters; bulk density in asterisks "*" and "**") ($n = 6$). The data are summarized as means ± standard deviations.

The bulk density of raw corncob before drying was 128.64 kg m^{-3}, after drying it was 153.74 kg m^{-3}, and the bulk density of the milled corncob ranged from 263.3 to 330.5 kg m^{-3}. The lowest bulk density was determined for the <1 mm fraction (in the dryer—263 ± 10.3 and in outdoor conditions—263.7 ± 2.0 kg m^{-3}), with no significant difference between them ($p < 0.05$, $n = 6$). No significant difference was also found between the remaining fractions for densities of 1.7 and 1.0 mm.

It was determined that the most adequate size for the milled biomass was 1 mm particles with a bulk density ranging from 327.4 to 330.5 kg m^{-3}. In conclusion, the results of the fractional composition of corncob biomass show that there was no significant difference between the different drying methods.

3.4. Analysis of Corncob Densification

Analysis of corncob densification was initiated by determining the effect of moisture content on density. The analysis was made for bulk materials and corncob pellets and is shown in Figure 7. The results show that the maximum bulk density was 350.98 ± 6.69 kg m^{-3} at 8.62% moisture content. The highest density of the densified pellets was 1012.96 ± 3.35 kg m^{-3} for a moisture content of 12.39%. A significant difference was found between all bulk density groups and pellet density groups (one-way ANOVA with the Tukey HSD test, $p < 0.05$, $n = 5$).

The relationship between moisture content and pellet compression ratio is presented in Figure 8. A significant difference was found between all compression ratio groups (one-way ANOVA with the Tukey HSD test, $p < 0.05$, $n = 5$). The highest pellet density of 1012.96 ± 3.35 kg m^{-3} was achieved at a moisture content of 12.39% in the raw material and a pressure of 780 MPa, with an average compression ratio of 3.43 ± 0.011 under these conditions. Increasing the moisture content of the pellets to 22.91% reduced the compression ratio to 2.72, which was 9.5% higher than that of the pellets with a moisture content of 5.99% (2.46 ± 0.008 for a bulk density of 862.26 ± 2.99 kg m^{-3} and pellet density of 330.5 ± 4.88 kg m^{-3}). The difference in compression ratio between pellets of 8.62% and 12.39% moisture content was 18.16% when the difference in pellet density was 2.8% (Figure 8).

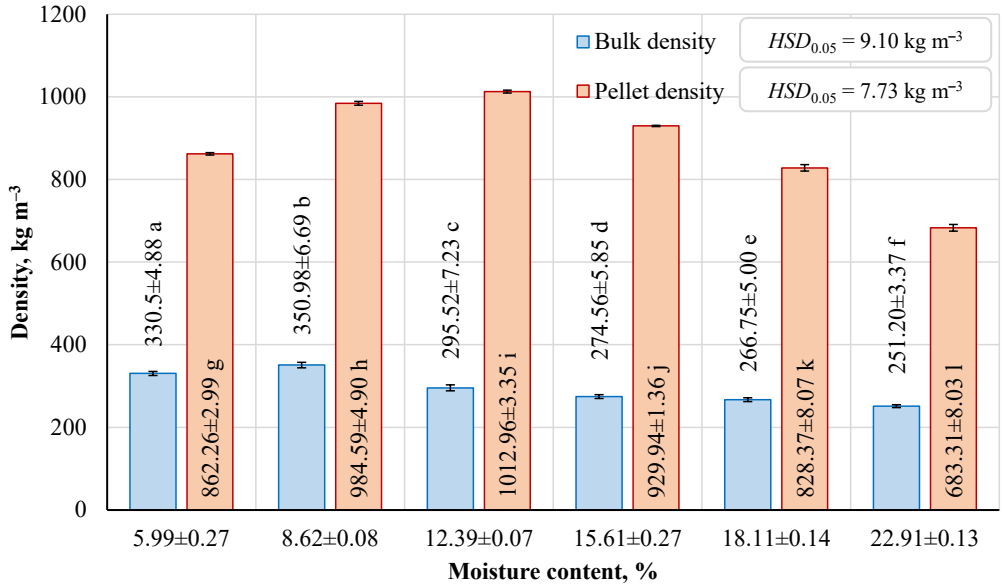


Figure 7. Dependence of corncob moisture on the bulk density and pellet density. Results are significant at $p < 0.05$ based on one-way ANOVA with the Tukey HSD test between bulk density groups ($n = 6$) and pellet density groups ($n = 5$) (lowercase letters). The data are summarized as means ± standard deviations.

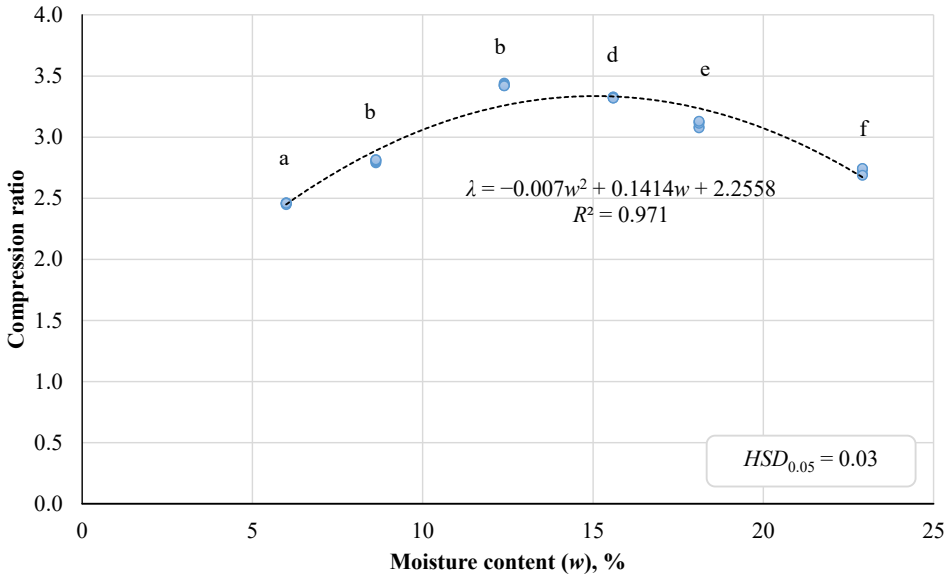


Figure 8. Dependence of the compression ratio on corncob pellet moisture. Results are significant at $p < 0.05$ based on one-way ANOVA with the Tukey HSD test ($n = 5$) for differences between groups (denoted by lowercase).

Comparing the average compression ratios of pellets with a moisture content of 8.62% and 15.61%, the average density of pellets with a moisture content of 8.62% (984.59 ± 4.90 kg m^{-3}) was about 5.55% higher than that of pellets with a moisture content of 15.61% (929.24 ± 1.36 kg m^{-3}); however, the average compression ratio was 17.18% lower (2.81 ± 0.014 and 3.39 ± 0.005, respectively). The average compression ratio of 15.61% moisture pellets (3.39 ± 0.005) was lower by 1.9% compared to pellets with 12.39% moisture (3.43 ± 0.011).

The compression ratio λ in Figure 8 can be described by the equation: $\lambda = -0.007w^2 + 0.1414w + 2.2558$. The coefficient of determination R^2 has a high value of 0.971, which confirms the model is a valid fit to the data.

The results (Figure 9) show how the density varies over time.

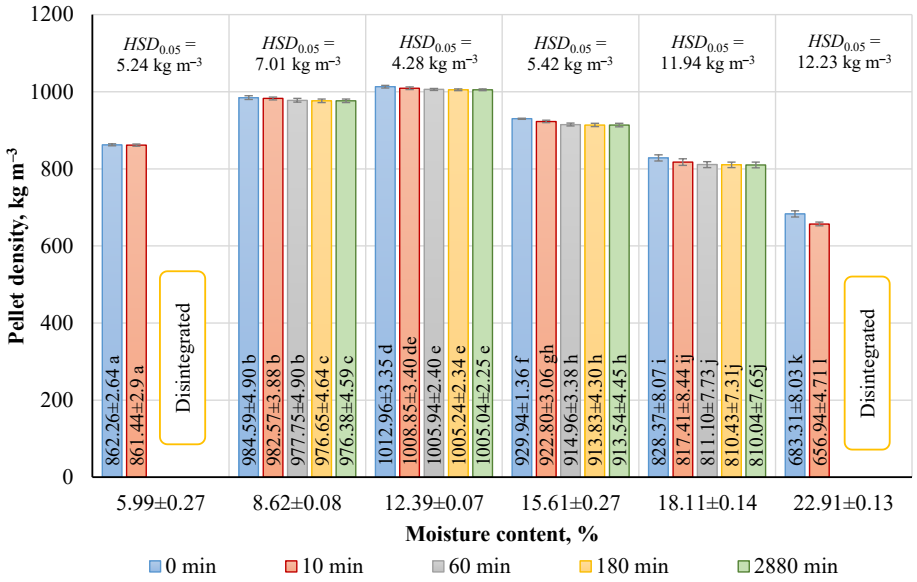


Figure 9. Variation in the density of corncob pellets at different times. Results are significant at $p < 0.05$ based on one-way ANOVA with the Tukey HSD test ($n = 5$), with differences between groups (denoted by lowercase letters). The data are summarized as means ± standard deviations.

The changes in dimensions were measured in the first hour, as shown by the significant differences between the first three measurements of 12.39%, 15.61%, and 18.11% moisture pellets (0, 10, and 60 min). For the pellets with a moisture content of 5.99%, there was no significant change in the dimensions, and no significant difference was found between them. Furthermore, these 5.99% samples, like the 22.91% moisture raw material pellets, disintegrated easily in the hand after 10 min of measurement. Observing the variation of the pellets, the 8.62% moisture pellets showed minimal splitting on the sides at the time of measurement (Figure 10), which could be explained by the lack of moisture. However, the shape was maintained. The lowest change in pellet density, between the first (0 min) and the last (2880 min) measurements, was recorded for the 12.39% moisture pellet at 0.78%. Between the first (0 min) and the last (2880 min) measurements, 8.62%, 15.59%, and 18.11% moisture pellets showed a change of 0.83%, 1.76%, and 2.21%, respectively. The highest change in pellet density was 3.86% with a moisture content of 22.91% (0–10 min).

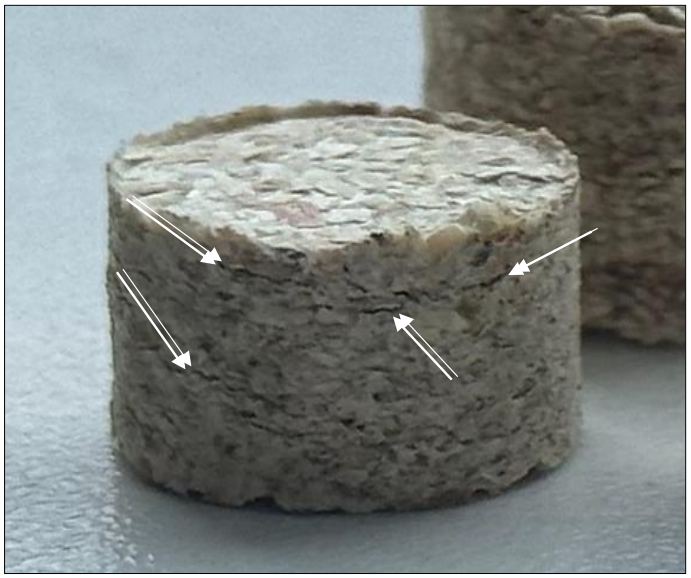


Figure 10. Side view of the 8.62% moisture pellet (cracks shown by arrows).

3.5. Analysis of the Compressive Strength of the Pellets

The results of the compressive strength tests analyzed for the selected fuel pellets with different moisture are presented in Figure 11.

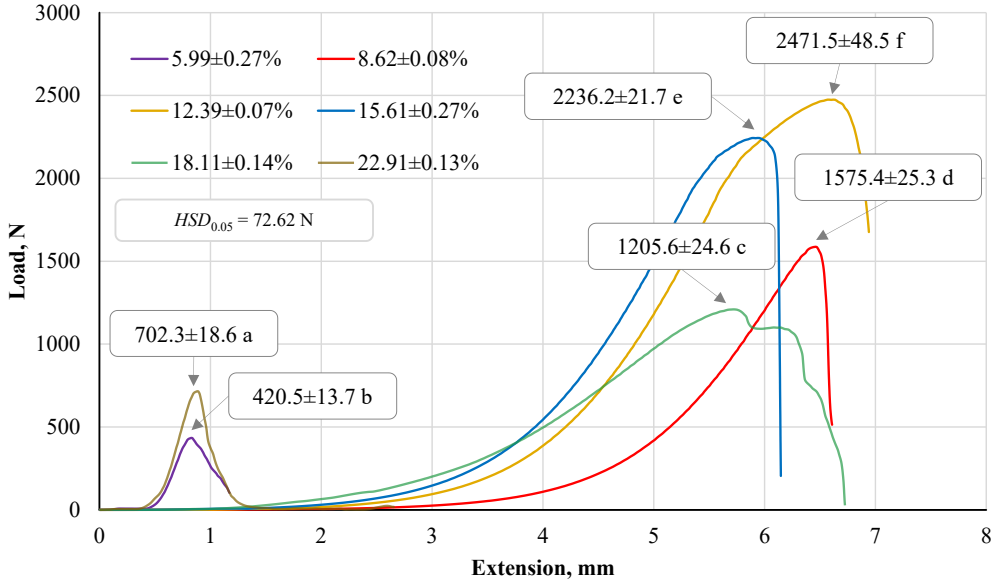


Figure 11. Compressive strength of corncob pellets. Results are significant at $p < 0.05$ based on one-way ANOVA with the Tukey HSD test ($n = 5$), with differences between groups (denoted by lowercase letters). The data are summarized as means ± standard deviations.

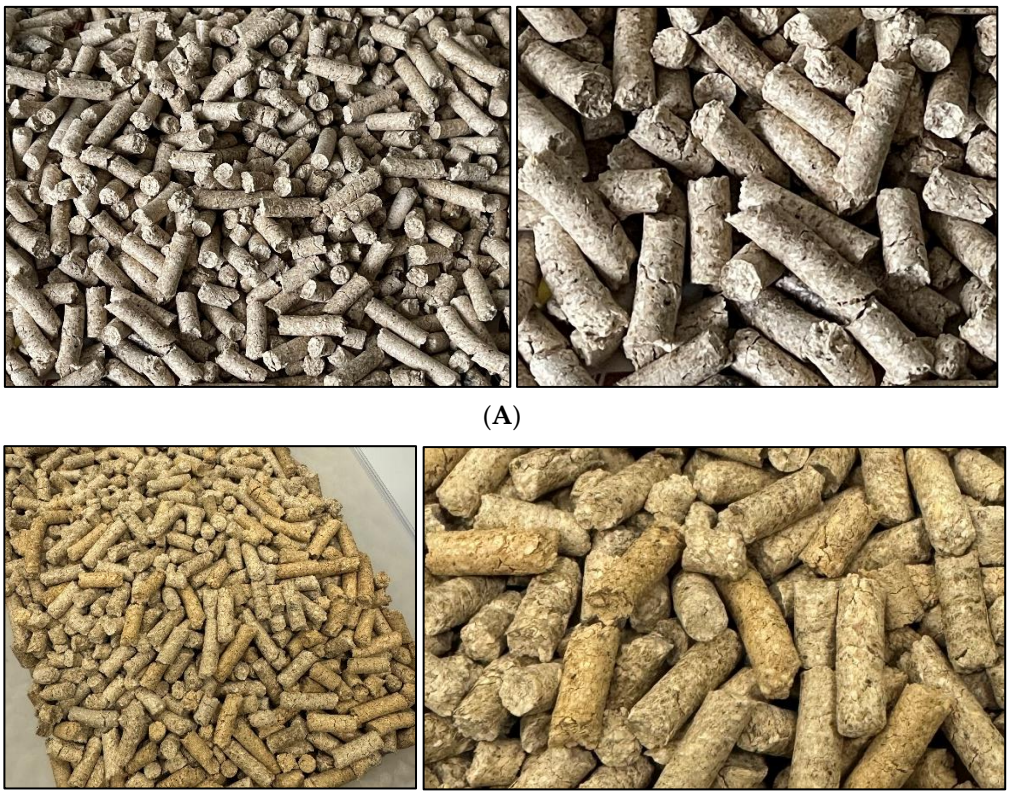
A pellet with a moisture content of 12.39 ± 0.07% reached the failure point at a load of 2471.5 ± 48.5 N. The compressive deformation was 2.66 to 6.57 mm before the pellet completely disintegrated. The pellet with a moisture content of 5.99 ± 0.27% resisted the lowest compressive force of 420.5 ± 13.7 N. The compressive deformation ranged from 0.016 to 0.172 mm. Similarly, a low compressive force of 702.3 ± 18.6 N was obtained for the pellet with the highest moisture content of 22.91 ± 0.13%, but the compressive deformation was longer, from 0.61 to 2.66 mm, compared to the lowest moisture content. Although significant differences were found between groups (one-way ANOVA with the Tukey HSD test, $p < 0.05$, $n = 5$), the closest compressive forces of 2236.2 ± 21.7 N and 2471.5 ± 48.5 N were seen in the pellets moisture content of 12.39 ± 0.07% and 15.61 ± 0.27%, respectively. However, the deformation time of the pellets differed; for example, at 15.61 ± 0.27% moisture content, the deformation occurred from 5.95 mm. At 8.62 ± 0.08% moisture content, with the previously mentioned cracks (Figure 10), the compression load of 1575.4 ± 25.3 N (6.47 mm) was required. For the pellets with the higher moisture content of 18.11 ± 0.27%, complete failure was observed at 5.70 mm with a load of 1205.6 ± 24.6 N. Based on the strength tests of the pellets, it can be assumed that the pellets did not contain an excessive amount of inorganic substances that could adversely affect the compression, structure, and strength of the pellets. The proper storage and transportation of the pellets would prevent damage to the pellets.

In summary, based on the effect of moisture on the density, compression ratio, and compressive strength of the pellets, it can be assumed that for different moisture contents of the pellets (5.99 ± 0.27%, 8.62 ± 0.08%, 12.39 ± 0.07%, 15.61 ± 0.27%, 18.11 ± 0.14%, and 22.91 ± 0.13%), the moisture content of 12.39 ± 0.07% pellets was found to be the best, with the highest values in the results. Although the 15.61 ± 0.27% moisture content pellets had lower parameters, the compression ratio (1.19%) and the compressive strength (9.52%) were the least distant from the 12.39 ± 0.07% moisture content pellets. Higher, but not excessive, moisture content (12–15%) led to the formation of pellets. This can be explained by the fact that the moisture in the raw material acted as a binding agent. The densification of the corncob pellets is thought to be influenced by the starch content, with better densification

of the pellets at higher moisture content. However, when the moisture content is too high (above 18%), compaction is reduced. At very low moisture content, the pellets no longer hold enough moisture and degrade. Thus, it can be concluded that the adequate moisture content for compaction of corncob raw material is around 12–15%.

3.6. Evaluation of Mass Production of Pellets

Based on the previous results, the most suitable moisture content of the milled corncob raw material 12.39 ± 0.07% was selected for further studies and pelleted in a horizontal matrix pelletizer. The moisture content of the pellets cooled after pelletizing in this way was 7.88 ± 0.16%. The main determined parameters of the pellets were as follows: the length of the pellets was approximately 11.69–30.81 mm, the average diameter of the pellets was 6.18 ± 0.061 mm (n = 12), the average density of the pellets was 1111.77 kg m^{-3} (n = 12), and the average bulk density of the pellets was 630.68 ± 0.81 kg m^{-3} (n = 6) (Figure 12).



(**A**)

(**B**)

Figure 12. Pellets compacted in a granulator with a horizontal matrix: (**A**) before the mechanical durability test; (**B**) after the mechanical durability test.

The compression ratio of these pellets was 9.75% (λ = 3.76) higher than the compression ratio of the pellets determined by the laboratory's automatic press. Although the moisture content was the same, friction in the granulator matrix heated the pellets at the same time, thus removing some of the moisture. The pellets were compressed but not heated as much when pelletized on the laboratory automatic press, and no significant difference in moisture content was observed ($p < 0.05$, n = 5). The choice of densification method and the temperature are considered to have an impact on the properties of the final product.

Figure 13 shows the results obtained after and before the assessment of the mechanical resistance, averaged over the fraction remaining on the sieve.

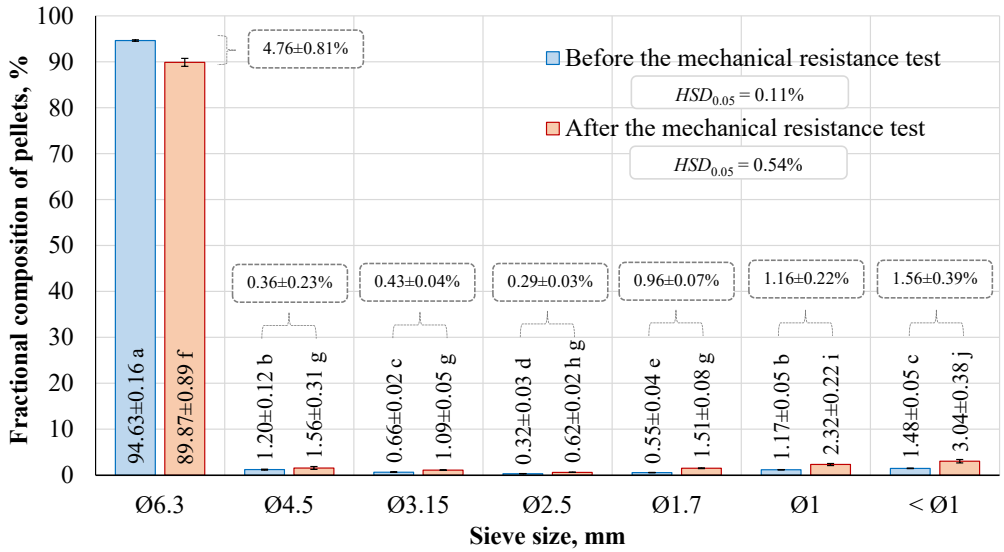


Figure 13. Evaluation of the brittleness of corncob pellets. Results are significant at $p < 0.05$ based on a one-way ANOVA with the Tukey HSD test ($n = 5$) for differences between groups (denoted by lowercase letters). The data are summarized as means ± standard deviations.

The 6.3 mm fraction of the mechanically analyzed material was 4.76 ± 0.81% of the total mass when exposed to corncob (Figure 13). The different fractions of the corncob pellets were irregularly distributed; e.g., the 4.5 mm fraction was 0.36 ± 0.23% of the total mass, while the corncob biomass with a size of 1 mm accounted for almost 69% more. It can be assumed that the particles of the material were subjected to strong forces during the mechanical resistance test and therefore broke down into smaller pieces. This change was most pronounced in the 1.7 mm size fraction, where the number of particles (1.51 ± 0.08%) increased by 63.57% after the mechanical resistance test, compared to the amount of material before (0.55 ± 0.04%). Also, after the mechanical resistance test, there was a 50% increase in dust content of 3.04 ± 0.038% and a decrease of almost 5% in the particle content of the largest particle size fraction of 6.33 mm by 89.87 ± 0.089%. Although in the raw material of the corncob pellets, both before and after the mechanical durability test, there was some cracking on the sides of the pellets (Figure 12), this did not have a significant effect on the degradation, as the pellets were firm and did not crumble under manual pressure. The pellets remained similar in size, with only scraping off the edges of the pellets.

According to the Lithuanian standard LST EN ISO 17831-1:2016 [35], particles passing through a 3.15 mm mesh sieve are considered dust (pellets with a size fraction < 3.15 mm). This fraction represents 3.52 ± 0.05% before the mechanical durability test and 7.48 ± 0.67% after the mechanical durability test of the total pellet content (the difference in recovery was 3.96 ± 0.66%).

Next, the lower calorific values of the corncob raw materials (initial milled corncob biomass; pellets with a size fraction > 3.15 mm; and pellets with a size fraction < 3.15 mm) were determined and are presented in Table 1.

The calculated lower calorific value of the studied initial biomass with a moisture content of 5.99 ± 0.03% was 17.20 ± 0.16 MJ kg^{-1}. After granulation, after separation into fractions, pellets with a size fraction > 3.15 mm (7.88 ± 0.16%) and pellets with a size fraction < 3.15 mm (8.48 ± 0.21%) had lower calorific values, respectively—17.35 ± 0.14 MJ kg^{-1} and 17.03 ± 0.34 MJ kg^{-1}. When evaluated statistically, using a one-way ANOVA with the Tukey HSD test, there was no significant difference between the lower calorific values of the raw materials ($p < 0.05$, $n = 16$).

Table 1. Indicators of lower calorific value and ash content.

Indicators	Initial Milled Biomass of Corncob	Fraction Composition of Pellets (>3.15 mm)	Fraction Composition of Pellets (<3.15 mm)
Moisture content, %	5.99 ± 0.03	7.88 ± 0.16	8.48 ± 0.21%
Lower calorific value after considering moisture content, MJ kg^{-1} *	17.20 ± 0.16 a	17.35 ± 0.14 a	17.03 ± 0.34 a
Ash content, %	1.78 ± 0.24	-	-

* $HSD_{0.05}$ = 0.65. Results are significant at $p < 0.05$ based on a one-way ANOVA with the Tukey HSD test (n = 16) for differences between groups (denoted by lowercase letters). The data are summarized as means ± standard deviations.

The average ash content of corncob was also determined, which was 1.78 ± 0.24%. In summary, we can say that the ash content and the calorific value in the material of corncob meet the requirements of the specifications of solid biofuel properties.

4. Discussion

The results of the corncob drying study showed that drying in an active ventilation dryer had a more uniform drying rate than drying in the field. However, although the drying rate was higher, the moisture content of the final product in the dryer was significantly higher than that of the field-dried corncob. The final average moisture content of corncob was about 15.8% in the field and 19.9% in the dryer. Aghbashlo et al. [38] showed that there are more than 400 different types of dryers. The choice of drying method depends on the material to be processed, the purpose, and the type of dryer. For each dryer, process conditions such as temperature, air flow rate, moisture content, and drying time of the product must be specified [39]. According to Pahla et al. [40], the moisture content of corncob was 10%, and the data obtained in this study are higher than those reported by Pahla et al. [40] and Gani et al. [41].

Zhu [42], in a study evaluating the performance of aerated barrel boxes, experimented with composting pig manure with corncob. Corncobs with a size of 5 cm were used in the study with a raw material moisture content of 17.6 ± 0.09% [42]. However, the results of research by Gani et al. [41] suggest that the moisture content of biofuel is lower than that of raw corncob. The authors show that the moisture content of raw corncob after drying in the sun for an unknown period is 12.44%, and that of corncob pellets is 7.72% (500 µm) compared with the results obtained for raw corncob of 15.8–19.9% and corncob of 22.3% (1 mm). Raw corncob moisture content of 7.70 ± 0.03% was obtained by Ibitoye et al. [43] in a briquette characterization study in which the collected corncob was sun-dried for 14 days in Ilorin, Nigeria.

In our study, we also observed that the relative humidity of corncobs decreases steadily under favorable weather conditions. However, in wetter (or rainy) weather, the moisture content of the corncob increases. This is determined by the weather conditions during drying. This result is confirmed by Reykdal [44] and Agarwal and Yadava [45], who show that the humidity and temperature of the field air affect the degree and duration of drying.

As for the density of dried corncob, at the beginning of the drying process, the bulk density of corncob was about 128.64 kg m^{-3}, while for dried corncob, it was 153.74 kg m^{-3}. Kaliyan and Morey [46] reported that the bulk density of corncobs varied within 163.9 ± 3.0 kg m^{-3} at 10% moisture content. In the case of our research, the results are 11.65% lower than those reported in the literature, but this may be influenced by the higher moisture content of corncob (17.87%), the different corncob variety used in the study, the growing conditions, and the harvesting time. The growth stage of corn has a direct effect on the bulk density of corncob.

Values of raw corncob cellulose reported in the literature range from 29.81% to 41.0%, according to Zhang et al. [47] and Gani et al. [41]. Similarly, 40% cellulose was also found in the corncob composition determination of Kaliyan and Morey [46] (Table 2). The lowest percentage of cellulose was found to be 29.81% by Zhang et al. [47]. The results obtained

for cellulose of 35.34 ± 0.11% drying in active ventilation dryers and 32.0 ± 0.94% drying in natural outdoor conditions are similar and in line with the results obtained by Gani et al. [41].

Table 2. Analysis of cellulose and hemicellulose.

Type of Biomass	Cellulose (% Dry Matter)	Reference	Hemicellulose (% Dry Matter)	Reference
Corncob (drying in active ventilation dryers)	35.34 ± 0.11		36.79 ± 0.95	
Corncob (drying in natural outdoor conditions)	32.00 ± 0.94		35.02 ± 0.45	
Raw corncob	29.81	Zhang et al. [47]	26.06 16.61	Gani et al. [41] Zhang et al. [47]
Corncob	40	Kaliyan and Morey [46]	41	Kaliyan and Morey [46]
Corncob	41	Gani et al. [41]	31.9 to 36	Cai et al. [48]

The amounts of hemicellulose measured vary according to the literature (Table 2). For example, Gani et al. [41] indicated a raw corncob hemicellulose content of 26.06%, while Cai et al. [48] argued that for the composition of lignocellulosic biomass, in this case, corncob, it ranged from 31.9 to 36%. A hemicellulose content of 41%, 1% higher than 40%, cellulose is given in the corncob compositional determination by Kaliyan and Morey [46]. The lowest hemicellulose value for raw corncob reported in the literature is 16.61% [47]. These parameters may vary from study as they depend on variety, growing conditions, and technology.

Comparing the results of both drying technologies, the amount of cellulose and hemicellulose in corncob dried in an active ventilation dryer is 7% and 4.8% higher, respectively, than corncob dried in outdoor conditions. Although the losses were not high, they are believed to have been influenced by the wet weather conditions outside on some days. According to Wang et al. [49], corncob hemicellulose losses were also attributed to the volatility of outdoor conditions and open storage, although they studied outdoor storage over 10 months, which resulted in losses of up to 20–50%. Atchison and Hettenhaus [50] reported a 30% dry matter loss in corn residue stored in the field over 3 months.

The starch content after outdoor drying (7.34 ± 0.14% dry matter) is 13.4% higher compared to the starch content obtained in the active ventilation dryer (6.36 ± 0.42% dry matter). In comparison with the studies of other researchers, it was observed that the corncob starch content was only 0.67% ± 0.12% dry matter according to the study by Pointner et al. [51], while the variation in maize cob dry matter content ranged from 455 to 524 g according to the study by Szyszkowska et al. [52]. Kaliyan and Morey [25] reported the effect of adding raw or pregelatinized starch on the strength and durability of the pellets. The researchers found that the pregelatinized starch increased the hardness and durability of the pellets to a higher degree than without the starch.

Kaliyan and Morey [46] showed that the bulk density of the milled biomass of corncob used ranged from 229.0 to 316.3 kg m^{-3}, and the particle size ranged from 0.85 mm to 2.81 mm. The authors also report that at a moisture content of 10.4%, the bulk density of corncob was 163.9 ± 3.0 kg m^{-3}. So there is no significant difference between drying in a dryer and drying in outdoor conditions for milled corncob biomass. The adequate geometric particle size for pellet production is the 1 mm fraction, for which a maximum density between 327.4 ± 3.34 and 330.5 ± 4.9 kg m^{-3} was obtained. The obtained bulk density is higher than the values reported in the literature, which may vary due to the moisture content of the biomass, the variety of corncob, and the fractional composition. Ibitoye et al. [53] relate changes in density to particle size and suggest that density increases with decreasing particle size.

The best parameters were found for pellets with a moisture content of 12.39%, a compression ratio of 3.43 ± 0.011, and a density of 1012.96 ± 3.35 kg m^{-3}, with the smallest change in pellet density of 0.78% (from 0 to 2880 min), and a compressive strain of 2471.5 ± 48.5 N (from 2.66 to 6.57 mm). It was also found that the compression ratio of 1.19% and the compressive strength of 9.52% for the 15.61 ± 0.27% moisture content pellets were the least distant from the 12.39 ± 0.07% moisture content pellets. Thus, 12–15% resulted in better pellet formation. The literature lacks specificity regarding the moisture content and the physico-mechanical properties of the compacted corncob raw material. Ibitoye et al. [53] evaluated briquettes of rice husk and corncob blends dried for 3 days (100:0, 80:20, 70:30, 60:40, and 50:50). It was found that density increases with increasing compaction force and rice husk content in the blend and with decreasing particle size; durability increases with finer particle size and is directly related to compaction pressure; and fracture and impact resistance decreases with increasing corncob fraction and particle size [53]. However, it is very difficult to judge because the moisture content of the compacted raw material, for both rice husk and corncob, is not clear. A literature review by Kaliyan and Morey [25] suggests that corncob of 8–20% moisture content with a particle geometric diameter of 0.5 to 1.0 mm leads to compacted products with high density and durability. The literature reports results on how corncob pelletization can increase their bulk density up to 550 kg m^{-3} [54], which is also confirmed by Kaliyan and Morey [46], who added that the production of pellets from corncob produces biofuels with a density of 500 to 600 kg m^{-3}. According to the research of Oladeji [55], studies showed that the initial, maximum, and resting densities ranged from 151 to 235 kg m^{-3}, 533 to 981 kg m^{-3}, and 307 to 417 kg m^{-3} for briquettes made from white corn, respectively. The corresponding values for yellow corn were 145 to 225 kg m^{-3}, 502 to 871 kg m^{-3}, and 314 to 464 kg m^{-3}, respectively, and the compaction factor ranged from 2.27 to 6.50 and 2.23 to 6.01 for briquettes made from corncobs from white and yellow maize, respectively.

When evaluating the compressive deformation of pellets, which was the highest in 12.39 ± 0.07% moisture pellets, it reached 2471.5 ± 48.5 N. Unlike in the research of other authors, we can note that the analysis of this corncob index was not found. In studies of pellets from Artemisia dubia by Jasinskas et al. [56], when the density of the pellets was 1192.44 kg m^{-3} and the moisture content was 9.98%, the compressive strength withstood a pressure of 560.36 N. The compressive force of Sida pellets ranged from 557 to 356 N (when the humidity increased from 5% to 15%, the diameter of the pallets was 6.0 ± 0.3 mm) [57]. However, it can be assumed that this indicator was influenced by the size of the pellet under study (the diameter of the pellet ranged from 6.22 to 6.39 mm, and the average pellet length varied from 21.82 to 25.77 mm), since it was produced by a granulator. In the cases of our research, pellets of the same moisture produced by a laboratory press were more uniform (mass of pellets about 4 g, diameter of the pressing matrix—20 mm, pressure force of the laboratory press—780 MPa (245 kN)). The optimal density and diametrical compressive strength of yak manure biofuel pellets are 1502.02 kg m^{-3} and 0.57 kN at 230 MPa pressure, 6% humidity, and 4.5% binder additive [58].

The granulator influenced the better compaction of the corncob raw material (12.39 ± 0.07%), as indicated by a compression ratio of 3.76, which was 9.75% higher than that of the pellets produced by the laboratory automatic press. The main parameters of the pellets were determined as follows: the moisture content of the pellets after compaction was 7.88 ± 0.16%, the length of the pellets was about 11.69–30.81 mm, the average diameter of the pellets was 6.18 ± 0.061 mm, the average density of the pellets was 1111.77 kg m^{-3}, and the average bulk density of the pellets was 630.68 ± 0.81 kg m^{-3}. The moisture content was similar to that obtained by Aransiola et al. [27] for corncob briquettes, which ranged from 4.43 to 7.62% (db), but the loosening densities of the compaction briquettes ranged from 729 to 987 kg m^{-3}. The compression ratio was 9.75% (λ = 3.76) higher than the compression ratio of the pellets as determined by the laboratory's automatic press. This is thought to be due to the friction generated by the granulation of the matrix, which heats the pellets strongly, thus removing some of the moisture. The choice of compaction method

and the temperature are considered to influence the properties of the final product. This is supported by Wongsiriamnuay and Tippayawong [59], Okot et al. [60], Ibitoye et al. [61], and Ibitoye et al. [43], who suggest that process variables such as compaction pressure, stamping temperature, stamping size, stamping speed, and compaction time are important for the properties of the end product. And they highlight that densification impacts product quality, properties, and durability [59].

Mechanical durability tests showed a variation in pellet recovery of 3.96 ± 0.66% (particle size < 3.15 mm). More stable pellets were found in Stolarski et al.'s [62] study, where wood pellets were analyzed and the mechanical durability of coniferous pellets was 99.6 and 97.7%. Also, fuel pellets made from sage waste biomass with the addition of rye bran pellets showed a better mechanical durability index, which was from 97.01 to 98.14% [63]. The resulting corncob lower calorific value was 17.35 ± 0.14 MJ kg^{-1}, and the ash content was 1.78 ± 0.24%. The lower calorific value of the biomass studied was calculated to be 17.35 ± 0.14 MJ kg^{-1}, which is lower than the calorific value of 18.17 ± 0.12 MJ kg^{-1} for corncob reported by Zhang et al. [64]. Jeguirim and Khiari [65] reported calorific values for corncob and oil palm trunk bark briquettes in the range of 16.54 to 16.91 MJ kg^{-1}. Studies by Cahyadi et al. [66] reported that properly processed corncob biomass pellets have a net calorific value of 16.5 MJ kg^{-1} or 3959 kcal kg^{-1} according to the SNI 8675:2018 standard [67] for biomass pellets. When comparing the calorific value of other alternative waste pellets, the studied coconut shells pellets, with a moisture content of 8.2%, had a higher heating value of 19.85 MJ kg^{-1} [68], which is 12.6% more than our studied raw materials of corncob. Piednoir [69], after carrying out experiments, noticed that granulation can increase the energy density of biomass. De Souza et al. [70], after conducting research with forest biomass (eucalyptus wood) and agricultural residues of coffee processing (parchment, silver skin, and coffee husk), determined that the moisture content directly affects the energy values of the pellets. In our case, we did not study the calorific values according to the moisture content, and, as can be seen, although the moisture content of the samples ranges from 5.99 to 8.48% (Table 1), the statistical evaluation showed that there was no significant difference between the results of the indicated calorific values.

The ash content of the corncob was found to be 1.78 ± 0.24%, with a similar result of 1.8% obtained by Kaliyan and Morey [46]. This confirms the claim of Zhang et al. [64] that the corncob ash content is less than 2%. Compared to the corncob ash content of 4.22% reported by Zhang et al. [47], the results obtained are 57.82% lower. Gani et al. [41] report raw corncob ash content of 2.58% and pellet corncob ash content of 2.78%.

To summarize the studies, it can be concluded that when producing pellets for biofuel, the moisture content of the crushed raw corncob material is very important and influences the efficiency of the pelletizing process.

5. Conclusions

Drying corncob biomass in a dryer with active ventilation was superior to outdoor drying. The results of the corncob drying methods showed slight changes in dry matter but no significant difference in fractional composition. The results for compaction, durability, and compression showed that the more adequate moisture content for compaction of the corncob raw material was 12–15%. To summarize the studies, it can be concluded that when producing pellets for biofuel, the moisture content of the corncob-milled raw material is very important in affecting the efficiency of the pelletizing process. Pellets, produced from 12.39 ± 0.07% moisture corncob, have sufficient strength and can be used for combustion. Thus, this provides an opportunity to understand the properties of corncob and evaluate its potential in the field of energetics.

Future research will focus on deeper chemical composition analysis during combustion and the characteristics and fusibility of the ash produced. Based on the results of these and further studies, a comparative assessment of the environmental and energy impacts of different treatment technologies is also planned. This should be carried out to better

understand the potential of corncob feedstock and the efficiency and sustainability of its use in industry.

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