

## Article

# Co-Pelletization of Rice Husk and Corncob Residues: Evaluation of Physicochemical Properties and Combustion Performance

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## Abstract

This study aimed to assess the physical, chemical, and combustion properties of pellets made from corncob and rice husk residues sourced in Sucre, Colombia, and to evaluate the performance of different blending ratios. Before pelletization, the residues were ground and processed using a small-scale flat die pellet mill equipped with a 6 mm die. Physical properties were evaluated according to ISO standards for particle density, bulk density, and impact resistance assessment. Proximate and ultimate analyses, as well as heating values, were determined and compared against the ISO 17225-6:2021 classification for herbaceous biomass. The 70:30 corncob-to-rice husk blend (CC70:RH30) showed good quality, with 7.23% ash, 9.18% moisture, and an LHV of 15.19 MJ/kg, meeting the criteria for Class B pellets. Combustion performance was assessed using a custom-designed macro-TGA, revealing that co-pelletized blends exhibited improved ignition temperatures and comprehensive combustion indices compared to the individual feedstocks. Additionally, calorific values were proportional to the blending ratios. In summary, controlling the blending ratio of corncob and rice husk residues during pellet production allows modulation of both the total ash content and the lower heating value of the resulting solid biofuels, making them more suitable for thermochemical conversion routes such as combustion and/or gasification.

**Keywords:** agro-industrial biomass; characterization; pellet quality; solid biofuel; residual biomass blends



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## 1. Introduction

Currently, global energy security still relies heavily on fossil fuels, despite their finite reserves, substantial ecological impacts, and direct contribution to climate change [1]. Hence, diversifying the energy mix has become a critical priority [2], and the valorization of agro-industrial residues is one of the main ways to achieve this goal because of their high availability [3]. Additionally, the large-scale accumulation of these residues produces significant environmental pollution through uncontrolled decomposition, greenhouse gas emissions, and potential soil and water contamination [4,5]. Applying the circular economy

framework contributes to transforming it from an environmental liability into a valuable resource, promoting closed-loop material flows, minimizing waste, and maximizing resource efficiency [6]. Integrating these concepts into biomass valorization strategies not only addresses environmental concerns but also strengthens the transition towards low-carbon, sustainable energy systems.

Lignocellulosic biomass represents one of the most widespread and oldest utilized sources of bioenergy worldwide [7,8]. However, their direct use as feedstock in thermochemical processes is often limited by their low energy density, unstable combustion characteristics, and challenges associated with storage and transport [9]. Pelletization is one of the most effective methods for converting lignocellulosic biomass into efficient solid biofuels, improving their transport and conservation characteristics [10]. Pellets have a significantly higher bulk density, which facilitates long-distance transport and prolonged storage [11,12]. Moreover, converting lignocellulosic biomass into biofuel pellets represents a viable strategy for reducing regional waste generation [3,13,14]. However, to ensure sustainable production, these pellets must meet quality standards [15]. These are not always achieved for a single residue or biomass. Sarker et al. [16] pointed out that co-pelletization of two or more biomasses can improve the thermophysical properties of fuel pellets. Co-pelletization contributes to expanding the exploitation of raw materials for pellet production, thereby reducing production costs and, consequently, their market price [17]. Previous studies indicate that co-pelletization between different lignocellulosic residual biomasses could contribute to the development of pellets with improved characteristics for bioenergy generation [18,19].

In this regard, Brand et al. [20] studied the co-pelletization of rice straw (RS), rice husk (RH), and pine shavings (PV), producing pellets using blends of 75% VP and 25% RS, 75% VP and 25% RH, as well as control treatments with 100% VP and 100% RS. They investigated the physical, mechanical, proximate, and energetic properties. Iglesias Canabal et al. [21] explored the elemental composition of pellets produced from blends of debarked *Pinus radiata* and *Eucalyptus nitens* wood in three different ratios: 100% pine, 90% pine and 10% eucalyptus, and 60% pine and 40% eucalyptus [17]. da Silva et al. [22] evaluated how the physical and chemical composition of different lignocellulosic biomasses influences pellet properties in Brazil, using both pure biomasses and binary blends in specific proportions. The study included elephant grass (*Pennisetum purpureum*), sugarcane bagasse, and eucalyptus sawdust. Seven types of pellets were formulated: three from pure biomasses (100% elephant grass, 100% bagasse, and 100% eucalyptus sawdust) and four from binary blends in 50:50 and 75:25 ratios between elephant grass and the other two biomasses. Vitoussia et al. [23] produced three pellet formulations, combining palm nut shells (PNS), palm mesocarp fibers (PNF), and coffee husks (CH). The three pelletized treatments consisted of ternary blends with the following ratios: 30% PNS + 60% PNF + 10% CH (30/60/10), 60% PNS + 30% PNF + 10% CH (60/30/10), and 45% PNS + 45% PNF + 10% CH (45/45/10), which were characterized through ultimate, proximate, and energy analyses.

Hossain et al. [24] reported on the quality assessment of pellets obtained from blends of three herbaceous energy crops: miscanthus (MS), corn stover (CS), and switchgrass (*Panicum virgatum*, SW). Five formulations were produced: 100% miscanthus pellets, 75% MS–25% CS, 50% MS–50% CS, 75% MS–25% SW, and 50% MS–50% SW, aiming to characterize the effect of co-pelletization on the physical, mechanical, chemical, and energy properties of the solid biofuel. Ríos-Badrán et al. [25] characterized three types of pellets: 100% RH, 75% RH + 25% wheat straw, and 50% RH + 50% wheat straw. These formulations were evaluated under two initial moisture levels (21% and 23%). Zawislak et al. [26] developed six pellet formulations using chamomile residues, birch sawdust, and pea and soybean residues, and evaluated their physicochemical and mechanical properties. Kamga

et al. [27] assessed the physical and energy properties of pellets produced with Movingui sawdust (*Distemonanthus benthamianus*), maize spathes, and coconut shells (*Coco nucifera*), as well as their blends. In particular, five treatments were formulated: two consisting of individual biomasses (100% maize spathes and 100% Movingui sawdust) and three ternary blends: 60% coconut shells + 30% maize spathes + 10% Movingui sawdust; 60% Movingui sawdust + 30% coconut shells + 10% maize spathes; and an equivalent blend of all three lignocellulosic biomasses studied, which showed promising energy performance with higher heating values ranging from 22.76 to 23.75 MJ/kg.

Kumar et al. [28] studied the physical, mechanical, and energy properties of pellets made from 100% pearl millet cob and binary blends with corncobs or eucalyptus sawdust. The pellets made from binary blends were formulated in the following proportions: 50% pearl millet–50% eucalyptus sawdust, 75% pearl millet–25% eucalyptus sawdust, 50% pearl millet–50% corncobs, and 75% pearl millet–25% corncobs. The physical and energy properties of pellets produced from blends of pine sawdust and hazelnut shells in 70/30 and 90/10 ratios (*w/w*) were reported by Solís et al. [29], reporting the evolution of their thermal decomposition under N<sub>2</sub> and O<sub>2</sub> atmospheres. Nie et al. [30] assessed the thermal degradation of lignocellulosic biomass through macro-TGA for peanut shells and wood sawdust 100:0, 70:30, 50:50, 30:70, 0:100 blends. Yılmaz et al. [15] developed pellets consisting of 100% grass (GRS), 100% palm pruning residues (PPR), and a blend designated as AGR, which comprised 50% olive pruning and 50% vine pruning, and assessed their ultimate and proximate composition as well as density in the context of pellet quality evaluation. Brand and Jacinto [31] investigated the energy potential of lignocellulosic residues from apple tree pruning pelletized, both individually and in blends with wood residues (*Pinus* sp.). The treatments included: 100% apple pruning, 75% apple pruning/25% pine, 50% apple pruning/50% pine, 25% apple pruning/75% pine, and 100% pine. He et al. [32] reported on the effect of co-pelletization using corn stalks combined with walnut shells on the physical properties and mechanical behavior of the resulting solid biofuels. Binary blends were formulated in ratios of 90:10, 80:20, and 70:30, using walnut shells as the minor component. Compared to pellets produced from individual biomasses, those made from blends exhibited improved compaction capacity and required less energy for compression. Nyashina et al. [33] investigated the effect of co-pelletization on the physical, mechanical quality, and combustion behavior of pellets made of straw, pine sawdust, and sunflower husks. A binary blend of 70% sawdust and 30% straw was formulated, along with two ternary blends composed of 68.75% sawdust/28.75% straw/2.5% sunflower husk and 67.5% sawdust/27.5% straw/5% sunflower husk. Rajput et al. [34] evaluated binary blends of groundnut shells, sawdust, and leaf litter wastes, with blends prepared in proportions ranging from 20% to 60% by mass, depending on the lignocellulosic additive used.

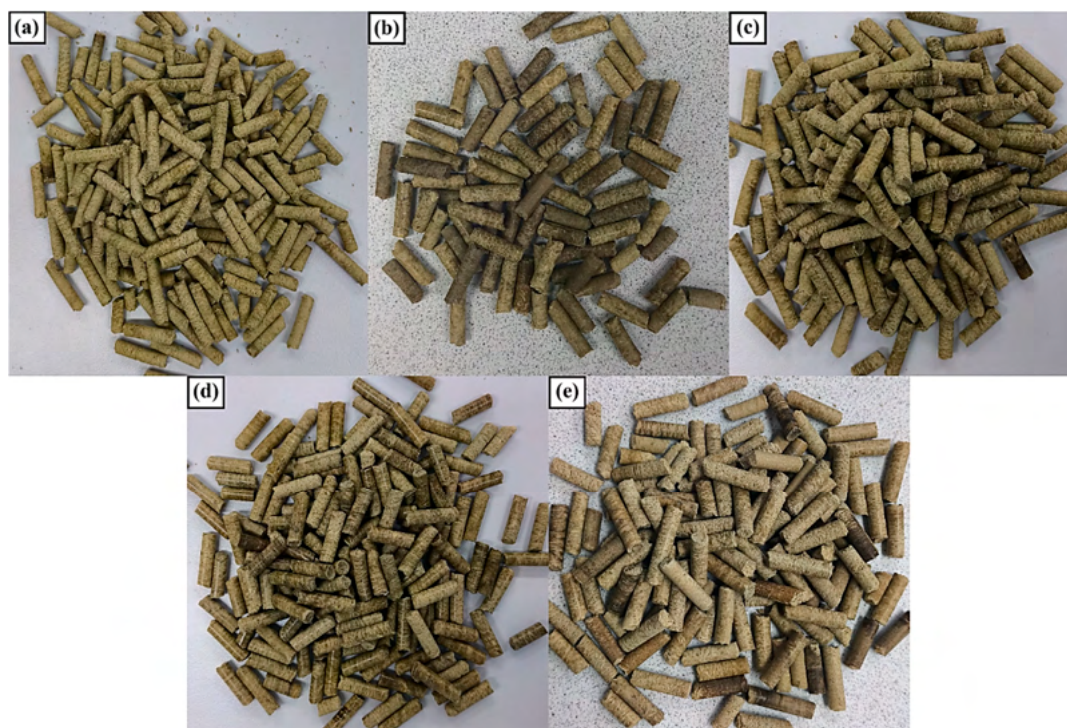
Co-pelletization of lignocellulosic biomasses stands out as a technological alternative for developing solid biofuels with high potential for bioenergy applications. However, to the best of our knowledge, there is no report in the literature about the co-pelletization of RH and corncob. Particularly, Colombia is the third largest rice producer in Latin America and the Caribbean [35]. Likewise, corn is a staple crop widely cultivated [36]. Specifically, in the departments of Sucre, Bolívar, Cesar, Magdalena, La Guajira, Atlántico, and Córdoba [37], rice and corn production in 2022 reached about 560,300 and 608,000 tons, respectively [38,39], generating an estimated 112,060 tons of RH and 164,160 tons of corncob as by-products [15,40]. Thus, there is significant energy potential from residual biomass in this region. Moreover, it is well known that RH exhibits higher ash content [25] than corncob [41]. Therefore, the co-pelletization of these residues could help modulate the resulting ash content by controlling the blending ratio, thereby contributing to the production of solid biofuels with higher commercial quality while promoting more sustainable

waste management practices. Consequently, this study aims to evaluate the physicochemical properties and combustion performance of pellets formulated from RH and corncob residues sourced from the department of Sucre, Colombia, at varying blending ratios.

## 2. Results

### 2.1. Physical Properties of Pellets

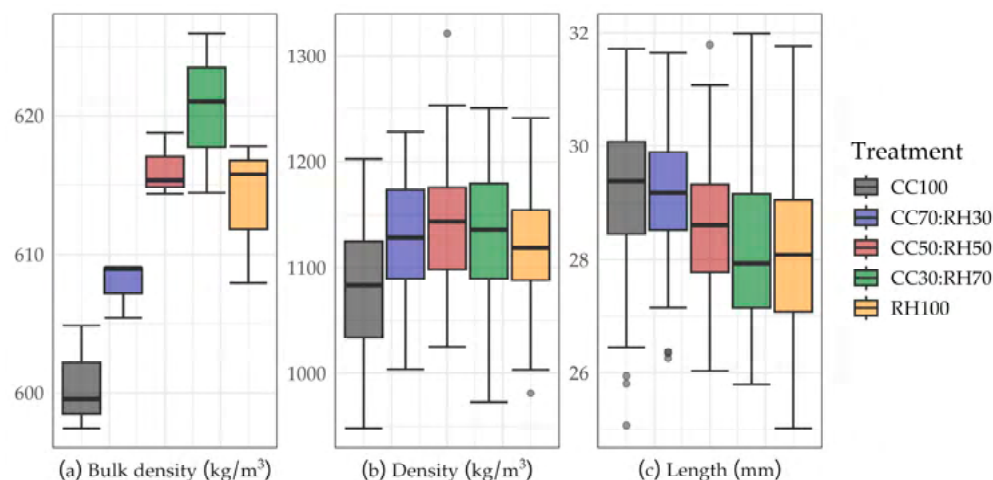
The studied pellets are shown in Figure 1; their diameter was 6 mm without significant dispersion. However, the other properties have a significant difference according to the biomass blend, as shown in Figure 2a. For bulk density, there are differences according to the formulations. RH100 and CC100 showed statistically significant differences in bulk density ( $p < 0.05$ ), indicating that RH100 achieved greater compaction efficiency. Furthermore, the CC30:RH70 formulation has the highest bulk density among all treatments, followed by the CC50:RH50, suggesting that increasing the proportion of RH in the blend resulted in denser pellets. CC100 has the lowest bulk density among all treatments, highlighting the limited compaction characteristics of this biomass. Figure 2b also depicts that pellet densities according to formulation remained between 1000 and 1150 kg/m<sup>3</sup>. Density is a key parameter, as it directly affects both the energy density and the mechanical stability of pellets. The particle density of pellets of corncob blends showed values close to those reported for the individual residues. However, concerning pellet density, no statistically significant differences were observed among RH and its corncob blends, whereas CC100 differed significantly from all other treatments ( $p < 0.05$ ).



**Figure 1.** Corncob and RH pellets using a 6 mm flat die: (a) CC100; (b) CC70:RH30; (c) CC50:RH50; (d) CC30:RH70; (e) RH100.

Additionally, Figure 2c showed length results with significant variation according to the pellet formulations. The CC100 and CC70:RH30 treatments yielded pellets with the highest median lengths, indicating that pellets produced with corncob or a higher proportion of corncob tend to be longer. In contrast, treatments with higher RH content, such as CC30:RH70 and RH100, exhibited slightly shorter median lengths and greater

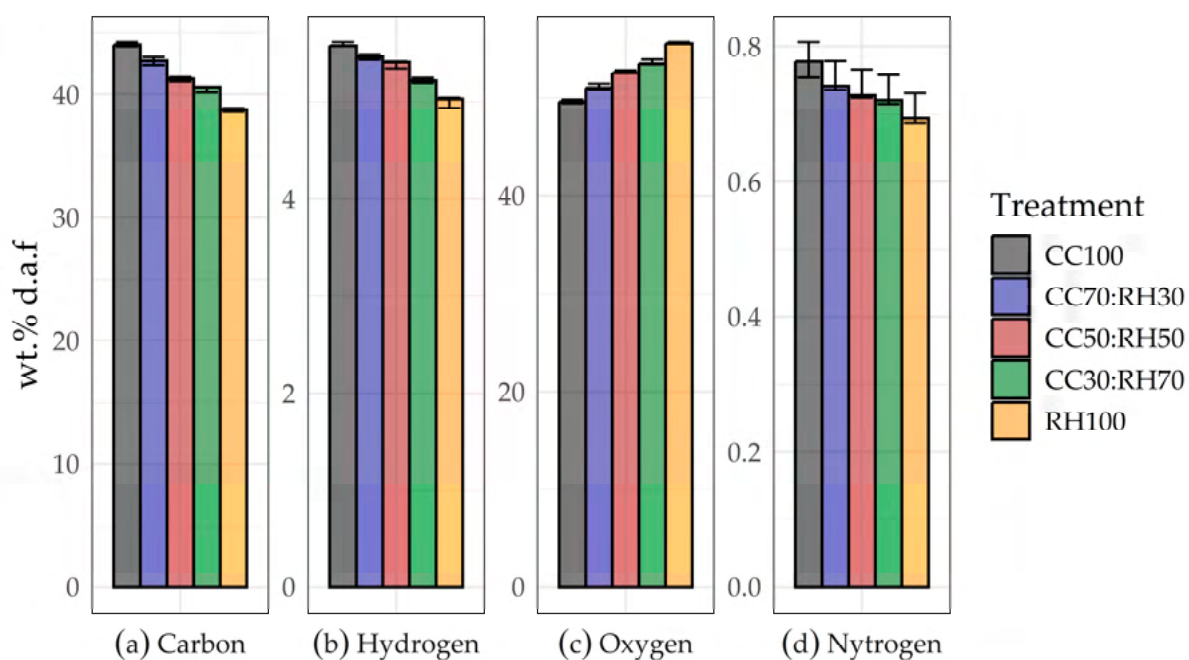
dispersion. Despite these differences, lengths remain within a relatively narrow range (approximately 26–32 mm), which is acceptable for commercial pellets.



**Figure 2.** Physical properties of corncob and RH pellets as a function of blending ratios: (a) Bulk density, (b) Pellet Density, and (c) Length.

## 2.2. Ultimate Analysis

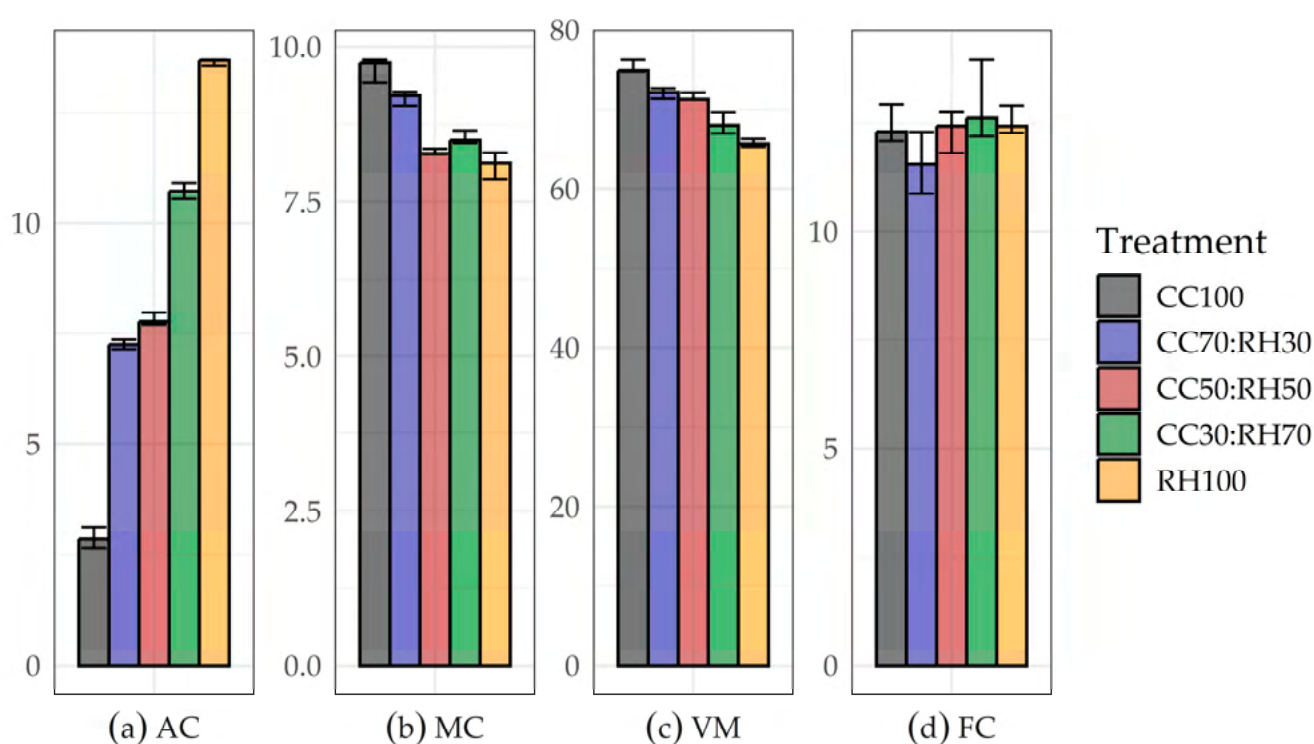
Figure 3a showed that pellets produced with 100% corncob (CC100) have the highest carbon content, at 44.02 wt.%. In contrast, RH100 pellets show a lower C content (38.75 wt.%) and H content (5.00 wt.%). In this way, carbon content exhibited a decreasing trend as the RH proportion increased. A similar behavior was observed for hydrogen in Figure 3b, which declined from 5.58 wt.% in CC100 to 5.00 wt.% in RH100. Nitrogen content was relatively low (<0.8 wt.%) but had a gradual decrease with increasing RH content, from 0.78 wt.% in CC100 to 0.70 wt.% in RH100. In contrast, oxygen content increased progressively with the proportion of RH, rising from 49.2 wt.% for CC100 to 54.7 wt.% for RH100. These compositional changes were consistent across the intermediate blending ratios of CC70:RH30, CC50:RH50, and CC30:RH70.



**Figure 3.** Comparative ultimate analysis of pellets produced from corncob and RH blends: (a) Carbon, (b) Hydrogen, (c) Oxygen, and (d) Nitrogen.

### 2.3. Proximate Analysis

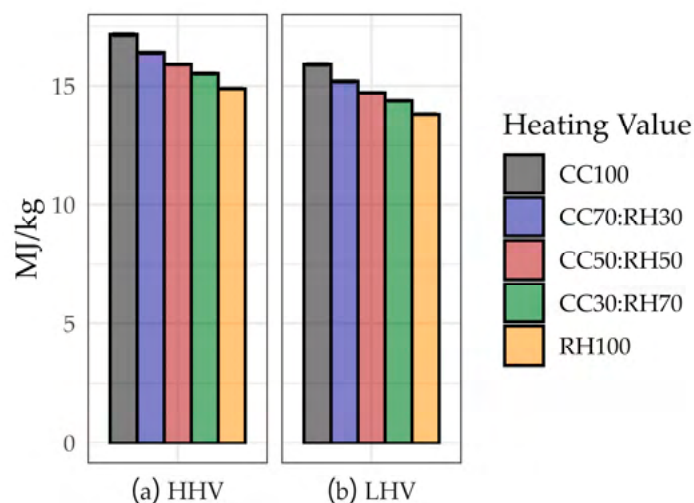
Figure 4 showed that the CC100 pellets have significantly lower ash content (AC) values compared to the RH100 pellets ( $p < 0.05$ ). Ash content is a critical parameter for fuel quality because high levels can decrease combustion efficiency and promote fouling in combustion systems [42]. The values range from around 3% for CC100 to about 13% for RH100, with intermediate blends showing gradual increases consistent with the proportion of RH. Regarding moisture content (MC), RH100 had the lowest with 8.2%, statistically different from CC100. In general, the MC of all pellets was below 10%, which is favorable for storage stability and combustion performance. CC70:RH30 and CC100 had the highest moisture from 9.2% to 9.8% (see Figure 4). Volatile matter (VM) content decreased slightly as the RH proportion increased, ranging from about 77% in CC100 to about 71% in RH100, which could influence ignition and burnout behavior. Fixed carbon (FC) values were relatively constant across treatments, between 10% and 11%, indicating that blending did not substantially affect this parameter.



**Figure 4.** Proximate analysis of pellets under different blending ratios: (a) Ash content (AC), (b) Moisture content (MC), (c) Volatile matter (VM), and (d) Fixed carbon (FC).

### 2.4. Heating Values

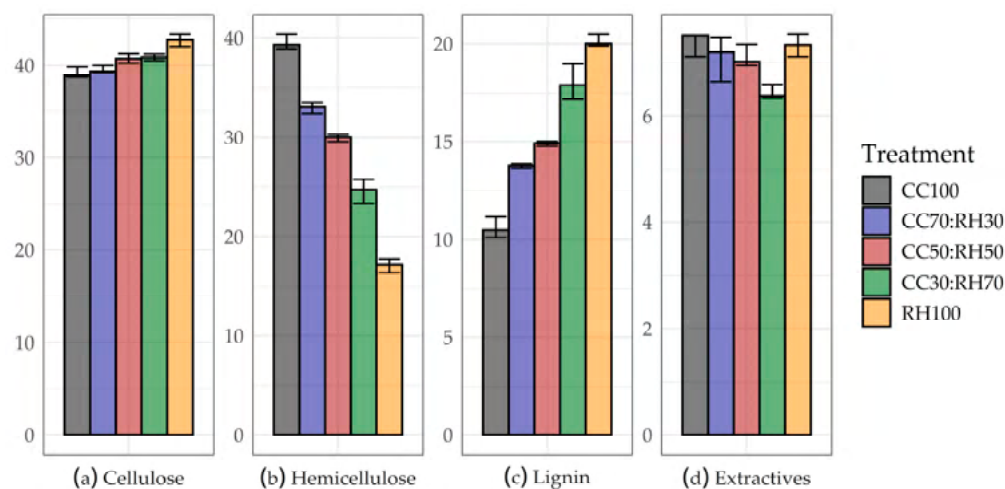
Figure 5 presents the heating values of the lignocellulosic pellets evaluated. CC100 exhibited the highest higher heating value (HHV) at 17.05 MJ/kg ( $p < 0.05$ ), followed by CC70:RH30, CC50:RH50, and CC30:RH70, while RH100 recorded the lowest HHV at 14.89 MJ/kg. A similar decreasing trend was observed for lower heating value (LHV), ranging from 15.90 MJ/kg for CC100 to 13.80 MJ/kg for RH100. The intermediate blends showed gradual reductions in both HHV and LHV, exhibiting general additive behavior.



**Figure 5.** Mean and lower heating values of pellets from different blending ratios: (a) Higher heating value (HHV) and (b) Lower heating value (LHV).

### 2.5. Chemical Composition

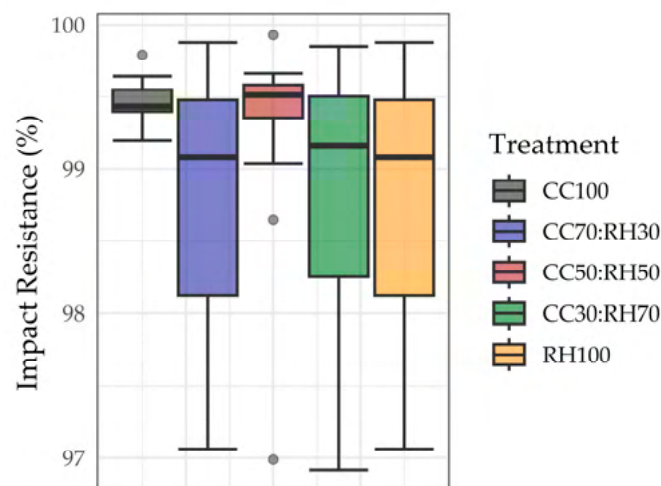
The chemical composition of the pellets varied significantly with the blending ratio of corncob and RH (Figure 6). Average cellulose content ranged from 39.2% for CC100 to 43.8% for RH100, showing a slight but consistent increase with higher RH proportions. Hemicellulose content displayed a marked decreasing trend, from an average of 38.23% in CC100 to 16.74% in RH100 ( $p < 0.05$ ). Average lignin content increased progressively with RH incorporation, from 11.01% in CC100 to 20.34% in RH100. Extractives content remained relatively stable across treatments, with values between 6.54% and 7.73%.



**Figure 6.** Cellulose, hemicellulose, lignin, and extractives content of lignocellulosic pellets from different blending ratios: (a) Cellulose, (b) Hemicellulose, (c) Lignin, and (d) Extractives.

### 2.6. Impact Resistance

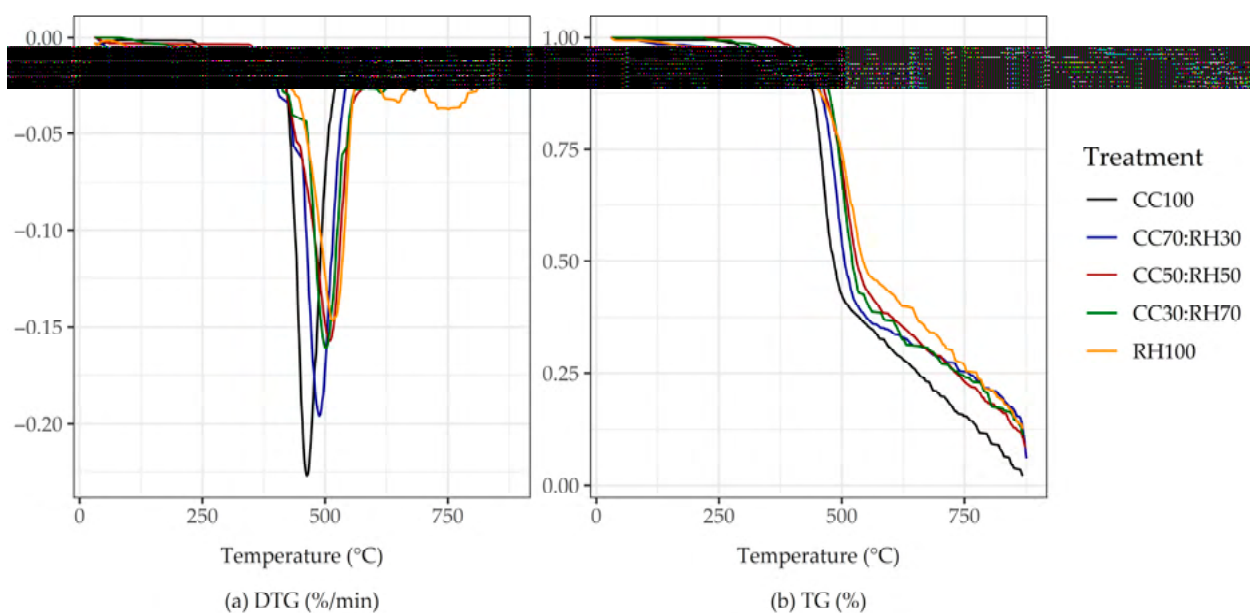
The impact resistance (IR) of the pellets for corncob and RH blending ratios is shown in Figure 7, evidencing high values between 98.7% to 99.5%, with excellent mechanical integrity under impact resistance. For all treatments, impact resistance remained above 97%, indicating high mechanical performance for handling and transport. Hence, the differences between treatments are marginal and within an acceptable range for commercial-grade pellets.



**Figure 7.** Impact resistance of the lignocellulosic pellets by treatment.

### 2.7. Macro-TG Analysis

Macro-TGA was used to assess the combustion behavior of the pellets under study. Figure 8a presents the derivative thermogravimetric (DTG) curves, which illustrate the rate of mass loss during thermal decomposition, while Figure 8b depicts the percentage of mass loss as a function of temperature.



**Figure 8.** Derivative thermogravimetric (DTG) and thermogravimetric (TG) profiles of corncob–RH pellets under different blending ratios: (a) DTG (%/min) and (b) TG (%).

The ignition temperature ( $T_i$ ), peak temperature ( $T_p$ ), burnout temperature ( $T_b$ ), flammability index ( $FI$ ), and comprehensive combustion index ( $CCI$ ) for the pellets produced from different RH and corncob blending ratios are shown in Table 1. The DTG curves show differences in peak temperature ( $T_p$ ) among treatments, from 459 °C for CC100 to 515 °C for RH100. Ignition temperature ( $T_i$ ) varied from 308 °C for CC70:RH30 to 377 °C for CC50:RH50. Burnout temperature ( $T_b$ ) ranged between 557 °C for CC30:RH70 and 614 °C for CC50:RH50. The flammability index ( $FI$ ) showed the highest value for RH100 ( $3.48 \times 10^{-6} \text{ \%} \cdot \text{min} \cdot \text{K}^{-2}$ ) and the lowest for CC100 ( $2.65 \times 10^{-6} \text{ \%} \cdot \text{min} \cdot \text{K}^{-2}$ ). Similarly, the comprehensive combustion index ( $CCI$ ) was highest for RH100 ( $3.14 \times 10^{-9} \text{ \%}^2 \cdot \text{min}^{-2} \cdot \text{K}^{-3}$ )

and lowest for CC100 ( $1.83 \times 10^{-9} \text{ \%}^2 \cdot \text{min}^{-2} \cdot \text{K}^{-3}$ ). Intermediate blends exhibited gradual changes in all combustion parameters between the two pure biomass types.

**Table 1.** Combustion characteristics of pellets under different ratios.

| Parameter/Treatment                                                               | CC100 | CC70:RH30 | CC50:RH30 | CC30:RH70 | RH100 |
|-----------------------------------------------------------------------------------|-------|-----------|-----------|-----------|-------|
| $T_i$ (°C)                                                                        | 343   | 308       | 377       | 376       | 345   |
| $T_p$ (°C)                                                                        | 459   | 487       | 512       | 500       | 515   |
| $T_b$ (°C)                                                                        | 586   | 576       | 614       | 557       | 601   |
| $FI$ ( $\text{\%} \cdot \text{min} \cdot \text{K}^{-2}$ ) $\cdot 10^{-6}$         | 2.65  | 3.16      | 3.13      | 2.98      | 3.48  |
| $CCI$ ( $\text{\%}^2 \cdot \text{min}^{-2} \cdot \text{K}^{-3}$ ) $\cdot 10^{-9}$ | 1.83  | 2.68      | 2.55      | 2.48      | 3.14  |

$T_i$ : ignition temperature;  $T_p$ : peak temperature;  $FI$ : flammability index;  $BI$ : burnout index;  $CCI$ : comprehensive combustion index.

### 2.8. Pellet Quality Analysis

The quality parameters of the pellets, assessed according to ISO 17225-6 [43], are summarized in Table 2. Pellet diameter was almost uniform ( $6.00 \pm 0.02$  mm), fulfilling the standard range of 6–10 mm. Pellet length from  $28.6 \pm 1.2$  mm for CC50:RH50 to  $29.2 \pm 1.3$  mm for CC100, meeting the standard limits of 3.15–40.00 mm. AC increased progressively with higher RH proportions, from  $3.2 \pm 0.9$  wt.% for CC100 to  $13.6 \pm 0.2$  wt.% for RH100. Moisture was below the 12% threshold for all blends, ranging from  $9.6 \pm 0.1\%$  for CC100 to  $8.1 \pm 0.1\%$  for RH100. LHV decreased gradually with the RH share, from  $15.9 \pm 0.1$  MJ/kg for CC100 to  $13.8 \pm <0.1$  MJ/kg for RH100, although some blends exceeded the minimum requirement of 14.5 MJ/kg except CC30:RH70 and RH100. Bulk density values exceeded the 600 kg/m<sup>3</sup> standard for all treatments, with CC30:RH70 showing the highest value at  $620 \pm 6.8$  kg/m<sup>3</sup> and CC100 the lowest at  $601 \pm 3.8$  kg/m<sup>3</sup>. Sulfur was not detected in any treatment, remaining below the 0.2% threshold. Nitrogen content was low in all blends, below 0.8%, with no statistically significant differences among treatments.

**Table 2.** Pellet quality parameters according to ISO 17225-6 standard.

| Treatment                         | ISO 17225-6 | CC100            | CC70:RH30        | CC50:RH50        | CC30:RH70        | RH100            |
|-----------------------------------|-------------|------------------|------------------|------------------|------------------|------------------|
| D (mm)                            | 6–10        | $6.00 \pm 0.02$  | $6.00 \pm 0.02$  | $6.00 \pm 0.02$  | $6.00 \pm 0.02$  | $6.00 \pm 0.02$  |
| L (mm)                            | 3.15–40.00  | $29.2 \pm 1.3$   | $29.1 \pm 1.2$   | $28.6 \pm 1.2$   | $28.1 \pm 1.3$   | $28.1 \pm 1.2$   |
| AC (wt.% db.)                     | $\leq 6$    | $3.2 \pm 0.9$    | $7.2 \pm 0.1$    | $7.8 \pm 0.1$    | $10.8 \pm 0.2$   | $13.6 \pm 0.2$   |
| MC (wt.%)                         | $\leq 12$   | $9.6 \pm 0.1$    | $9.1 \pm 0.1$    | $8.2 \pm 0.1$    | $8.4 \pm 0.1$    | $8.1 \pm 0.1$    |
| LHV (MJ/kg)                       | $\geq 14.5$ | $15.9 \pm <0.1$  | $15.2 \pm <0.1$  | $14.7 \pm <0.1$  | $14.4 \pm <0.1$  | $13.8 \pm <0.1$  |
| Bulk Density (kg/m <sup>3</sup> ) | $\geq 600$  | $601 \pm 3.8$    | $608 \pm 2.1$    | $616 \pm 2.3$    | $620 \pm 6.8$    | $614 \pm 5.2$    |
| S (wt.% db.)                      | $\leq 0.2$  | n.d.             | n.d.             | n.d.             | n.d.             | n.d.             |
| N (wt.% db.)                      | $\leq 1.5$  | $0.78 \pm <0.03$ | $0.75 \pm <0.03$ | $0.74 \pm <0.03$ | $0.73 \pm <0.03$ | $0.70 \pm <0.03$ |

n.d: non-detected.

## 3. Discussion

### 3.1. Analytical Perspectives on Physical Properties

The evaluation of pellet length and diameter is crucial for pelletized biomass fuels, as they must meet the requirements of most industrial users, with diameters ranging from 6 to 8 mm [44]. Likewise, bulk density is a critical attribute that directly affects the efficiency of pellet transport, handling, and storage [45]. Although the average particle densities of all treatments ranged from 1000 to 1150 kg/m<sup>3</sup>, significant differences were observed in bulk density ( $p < 0.05$ ). The bulk density for CC100 was similar to that reported by Miranda et al. [46]. Increasing the proportion of RH resulted in the highest average bulk density, observed for CC30:RH70. A higher bulk density is desirable for pellet storage, handling, and transport, as it optimizes volumetric energy density and reduces logistic

costs [11]. Similar to  $1100 \text{ kg/m}^3$  for RH pellets made at 150 MPa, reported by C. Chen et al. [47]. Likewise, Wongsiriamnuay & Tippayawong [37] reported particle density values for corncob pellets of  $1026 \text{ kg/m}^3$ , which are close to the average density values for corncob pellets reported in this study ( $1067 \text{ kg/m}^3$ ). All treatments, however, showed particle densities above  $1000 \text{ kg/m}^3$ , consistent with good fuel quality [10]. These results evidence that co-pelletization improves the physical properties of the pellets, particularly bulk density, by combining the structural and binding characteristics of both lignocellulosic residues. These findings are in accordance with previous studies reporting that blending lignocellulosic feedstocks can enhance pellet packing efficiency [24].

### 3.2. Insights from Ultimate Analysis

The elemental composition of pellet fuels has significant implications for their performance in thermochemical processes. The balance of carbon (C), hydrogen (H), and oxygen (O) is critical for combustion quality and energy efficiency [41]. In particular, CC100 showed 13.59% higher average carbon content and 11.63% higher average hydrogen content than RH100. Similar findings have been reported for RH and corncob regarding their carbon and hydrogen contents [47,48]. Based on preliminary experiments, it was confirmed that the addition of 2% cassava starch did not significantly influence the C contents of the pelletized treatments. Sykorova et al. [49] similarly found that adding 2% starch or flour to meadow hay pellets did not alter the carbon content relative to the control. Yet, it did result in a measurable improvement in pellet hardness. Notably, increasing the RH proportion results in reduced C and H contents and a corresponding increase in O content, suggesting that the co-pelletization of corncob and RH can effectively modulate elemental composition, which may influence combustion performance. Nitrogen levels remain low and consistent for all treatments (0.70–0.78 wt.%), below 0.8% considered by Solís et al. [29] to be suitable for use in small-scale combustion plants, as  $\text{NO}_x$  emissions would be significantly low. These trends pointed to the need to optimize blending ratios to maximize energy yield while controlling undesirable emissions. The absence of sulfur in the treatments is particularly beneficial for thermochemical processes because of the reduction in corrosion risk. The intermediate RH proportions pellets, as CC70:RH30 or CC50:RH50, may result in a balance between fuel quality and resource utilization, combining the favorable energy characteristics of corncob with the availability and low cost of RH.

### 3.3. Evaluation of Proximate Analysis

Proximate analysis of biomass evaluates moisture, volatile matter, ash, and fixed carbon to quantify its net energy content [50]. Moisture is a critical parameter in determining biomass pellet quality because it influences combustion efficiency [51]. Usually, all fuel has a moisture content below 10%, suggesting the suitability of these densified solid biofuels for use in thermochemical processes. As expected, pellets with a higher proportion of RH show high ash content due to the high ash fraction of RH [25]. Specifically, the RH100 ash content is 10.34% higher than that of CC100. This increase in ash is a critical factor that can lead to operational issues such as slagging and fouling during combustion or gasification. However, Cao et al. [52] highlighted that the use of biomass blends can help reduce the total ash content, thereby preventing ash agglomeration; likewise, Awais et al. [53] reported that the combustion processes of biomass blends are more efficient, with lower ash contents and reduced tar yields when these are subjected to co-gasification. In this context, the production of solid biofuels through the co-pelletization of corncob and RH emerges as a viable strategy for valorizing residual lignocellulosic biomass blends with dissimilar ash contents. This approach enables modulation of the general ash content in the resulting solid biofuels by adjusting the biomass blending ratio [28]. Hence, according to AC content,

CC100 is more suitable for applications where low ash generation is required. Pellets produced from RH and corncob blends exhibited intermediate AC values, ranging between 7% and 12%. Intermediate blending ratios of CC70:RH30 and CC50:RH50 may result in a balance between low ash content and the availability and low cost of RH. The volatile material content influences the ease of ignition and combustion rate of biomass [54]. CC100 exhibited the highest average volatile matter content at 75%, which may contribute to rapid combustion. Pahla et al. [55] documented similar results. Notably, CC50:RH50 has an intermediate VM level (approximately 72%), which, combined with its low moisture content and  $AC < 8\%$ , could offer a balance between combustion efficiency and controlled burn rate compared to RH100. The variations in VM suggest distinct thermal properties across treatments, likely due to differences in feedstock composition. Fixed carbon refers to the carbon in biomass that remains as solid residue after combustion [56]. All treatments show comparable FC values, with a range from 11% to 13%, and no statistically significant differences among them. Similar results have been reported in previous studies for RH pellets [25].

### 3.4. Implications of Heating Values

The higher heating value (HHV) is critical for the energy content of fuels [57]. Corncob pellets (CC100) showed a mean HHV 14.97% higher than that of RH100. Similar values were reported by Miranda et al. [46] for corncob and by Islam et al. [58] for RH. This significant difference highlights the superior energy content of corncob compared to RH. Volli et al. [59] highlighted a high HHV for RH, associated with a cellulose content of 54.3% and a carbon content of 47.2%. However, the ash was notably low at 1.2%. The variations in pellet calorific value are a consequence of the biomass ash content; the high level in the RH decreases its calorific value compared to the low ash content in corncob. Additionally, the carbon in corncob was significantly higher than that in RH, which also explains the higher calorific value. Blended treatments displayed intermediate energy values, with HHVs ranging from 15.51 to 16.38 MJ/kg and LHVs from 14.37 to 15.19 MJ/kg. The gradual decrease in heating values with increasing RH content suggests that the lignocellulosic composition of each biomass influences the energy properties of the pellets. In summary, blends with high shares of corncob result in higher heating values, improving the thermochemical conversion efficiency. However, the reduction in HHV and LHV for intermediate corncob shares such as CC70:RH30 suggests that partial substitution with RH could be viable without significantly affecting fuel quality, particularly when considering energy content, feedstock availability, and waste valorization.

### 3.5. Relevance of Chemical Composition

Cellulose constitutes the primary fraction of most fuel-grade biomass. Consequently, lignocellulosic materials with elevated cellulose levels generally exhibit higher combustion efficiency, reducing energy recovery during thermal conversion [41]. Although RH100 has a higher cellulose content compared to CC100, it also has a higher ash content, limiting its energy valorization potential. Hemicellulose content varies widely, from 38.23% in CC100 to 16.74% in RH100, close to what is reported by Cai et al. [60] and Agar et al. [61], while Draszewski et al. [62] showed similar results for RH. Lignin content, critical for structural integrity, is at the highest level in 20.34% for RH100 and 11.01% for CC100 according to prior results [41,63]. The elevated lignin content in treatments with higher RH proportions may enhance pellet consistency and resistance to degradation, thereby improving storage and handling properties [28]. Therefore, these results are consistent with the highest average bulk density value observed at CC30:RH70. However, biomass with a high lignin content has lower combustion efficiency [41]. Hence, blending biomass with markedly different

lignin contents can be an effective strategy to adjust the overall lignin fraction in pelletized solid biofuels, thereby improving combustion performance. Combining corncob with RH balances the proportions of cellulose, hemicellulose, and lignin, enhancing pellet properties for bioenergy applications. Similar extractive contents for corncob and RH were reported by Awosusi et al. [64] and Quintero-Naucil et al. [65], respectively. In the present study, intermediate values were observed for pellets produced from blends of these biomasses, with no statistically significant differences detected ( $p > 0.05$ ).

### 3.6. Impact Resistance Analysis

Pellet impact resistance (IR) is assessed to consider the loading and unloading operations involved in the logistics of solid biofuels [66]. The consistently high IR values across all blends confirm that co-pelletization of RH and corncob offers an alternative approach to produce solid biofuels with sufficient mechanical properties for handling, transport, and storage. Similar results have been reported for other agricultural residues [16,28]. The performance of intermediate blends, particularly CC50:RH50 and CC30:RH70, suggests that incorporating RH at moderate levels does not substantially affect the physical integrity, likely due to the combined effect of the capacity of corncob and the inherent lignin content of RH, both of which contribute to structural integrity. The high resistance over 97% across all treatments indicates that these pellets can successfully support storage, transport, and feeding into thermochemical conversion systems.

### 3.7. Thermochemical Behavior from Macro-TG Insights

The thermal degradation patterns observed in the TG and DTG profiles are characteristic of lignocellulosic biomass, with a primary devolatilization stage driven by hemicellulose and cellulose decomposition, followed by slower lignin degradation. The onset of mass loss appears between 280 and 320 °C, with variations among different biomass blends. CC100 shows a sharper decline compared to RH100, indicating a higher volatile content in CC. Similar findings were reported by G. Guo et al. [67]. The lower ignition temperature observed for CC70:RH30 suggests enhanced reactivity at the onset of combustion, potentially due to synergistic interactions between the two feedstocks that facilitate volatile release. In contrast, the higher ignition temperatures of CC50:RH50 and CC30:RH70 may reflect increased thermal stability linked to higher lignin content. The elevated peak and burnout temperatures in RH-rich samples such as RH100 and CC50:RH50 indicate slower char oxidation, likely due to the higher silica and ash content of RH. This is consistent with the higher burnout temperatures observed in these treatments. The FI and CCI trends indicate that RH100 exhibited controlled combustion with a greater tendency to retain residual ash, suggesting that the mineral composition of RH may catalyze specific combustion reactions; however, its use could lead to slagging and agglomeration in combustion reactors. However, its lower heating value compared to CC100 (as shown in previous results) means that, while ignition and burnout may be rapid, the total energy yield per unit mass is lower. CC100, conversely, showed the lowest FI and CCI, reflecting slower ignition but potentially more stable combustion with a higher energy density. From a practical standpoint, intermediate blends, particularly CC70:RH30, appear to balance low ignition temperatures with moderate burnout rates and acceptable energy content. This balance could be advantageous for thermochemical conversion systems requiring rapid start-up without excessive loss of fuel reactivity or calorific performance.

### 3.8. Integrated Assessment of Pellet Quality Parameters

ISO 17225-6:2021 specifies that herbaceous biomass pellets classified as Class A and B must have lengths between 3.15–40.0 mm [46]. Accordingly, all pellets evaluated in this study met this quality standard. The diameter remains consistent across all treatments,

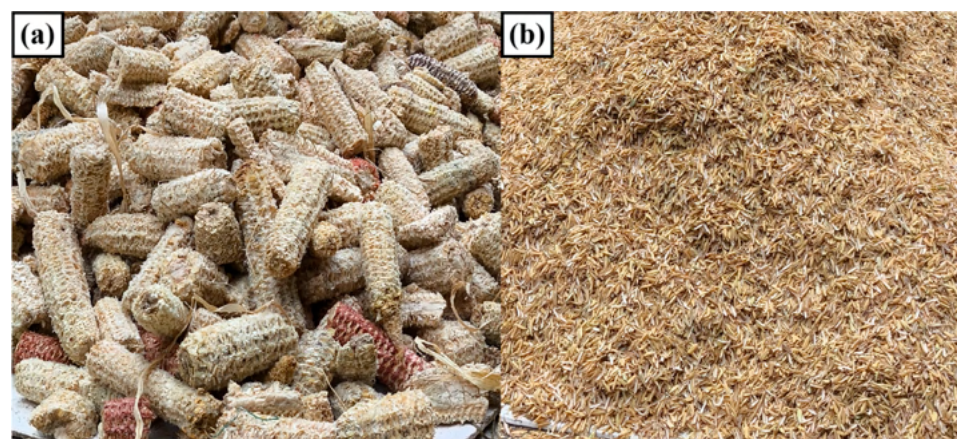
6 mm in each case. This uniformity implies that the flat die in the pelletizing equipment determines the diameter. The diameter across treatments is crucial for the mechanical consistency of the solid biofuel, as it enables predictable combustion behavior. For that reason, most industrial users of fuel pellets utilize biofuels with diameters between 6 and 8 mm [44]. Likewise, the international standard for herbaceous biomass pellets sets a nitrogen content limit of 1.5% to qualify for grade A. Therefore, all pellets evaluated in this study meet this requirement [43].

According to international standards for non-woody pellets, herbaceous biomass fuels are classified as grade A with an ash content lower than 6% and grade B with a maximum ash content of 10% [43]. Based on this, CC100 achieved Grade A quality, although its bulk density is at the threshold, which could compromise actual compliance with this parameter, while the rest of the treatments met Grade B standards. Although CC30:RH70 treatment showed an average ash content of 10.8%, its quality was close to the maximum limit for grade B ( $\leq 10\%$ ). Hence, CC70:RH30 meets all the quality parameters required to be classified as Class B pellets, confirming that co-pelletization is effective for producing commercially viable pellets. According to the international standard for herbaceous biomass pellet blends, grade A pellets must exhibit an LHV of at least 14.5 MJ/kg [43]. All treatments met grade A quality for moisture content according to the international standard for pellets from herbaceous biomass or biomass blends [43], with all pellets exhibiting moisture content below 12%. The findings of this study confirm that blending biomass in various proportions improves pellet quality. Specifically, class B pellets were achieved with CC70:RH30 according to ash content, bulk density, LHV, moisture content, and additive concentration, with a 2% mass fraction of cassava starch, which is below the international standard limit of 5%. Furthermore, particle density values for the evaluated treatments showed no statistically significant differences, indicating that pelletization of RH and corncob blends produced pellets with high particle density ( $>1000 \text{ kg/m}^3$ ). Therefore, pellets made from RH and corncob blends show great potential as solid biofuels with quality characteristics suitable for commercial applications.

## 4. Materials and Methods

### 4.1. Material Preparation

Pellets were produced using blends of RH and corncob residues, along with two control treatments consisting of 100% of each biomass individually. Both RH and corncob residues were generated in the department of Sucre, Colombia. Specifically, the RH was obtained from small mills located in the municipality of Majagual, while the corncob came from agricultural farms in the municipality of Colosó (Figure 9).

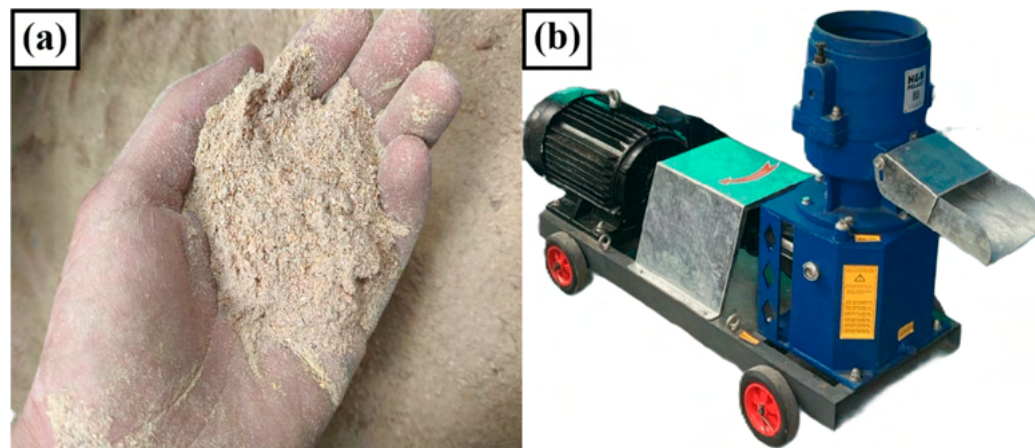


**Figure 9.** Raw biomass feedstocks: (a) corncobs and (b) RHs.

After collecting, each lignocellulosic residue was ground and sieved to achieve a particle size of less than 4 mm for characterization and processing into pellets.

#### 4.2. Pelletization Process

The RH and corncob were pelletized individually using a small-scale pelletizing machine (PELET YD 300, Henan, China) equipped with a flat die perforated with 6 mm diameter holes (see Figure 10), located at the Puerta Roja campus in the University of Sucre in Colombia. Additionally, based on the blending ratios reported in the specialized literature for co-pelletization of binary lignocellulosic biomass blends [20], the co-pelletization of both residues was performed in varying ratios: 50:50, 30:70, and 70:30, as shown in Table 3.



**Figure 10.** (a) ground material prior to pelletization and (b) biomass pelletizer.

**Table 3.** Proportions of corncob (CC) and rice husk (RH) in the experimental treatments.

| Treatment | CC: Corncob (%) | RH: Rice Husk (%) |
|-----------|-----------------|-------------------|
| CC100     | 100             | 0                 |
| RH100     | 0               | 100               |
| CC70:RH30 | 70              | 30                |
| CC50:RH50 | 50              | 50                |
| CC30:RH70 | 30              | 70                |

For all treatments, 2% cassava starch was added to each blend before pelletization to improve pellet firmness and compaction. The ground material was dried to 20% *w/w* of humidity before pelletization (Figure 10a). Based on preliminary trials, it was determined that a moisture content of 20% *w/w* for the biomasses, combined with a stabilization period of 15 h before pelletization, resulted in efficient pellet production for corncob and RH studied.

Finally, the resulting pellets were subjected to solar drying under atmospheric conditions using natural convection for 15 min [33]. Afterward, the pellets were stored in airtight plastic bags for subsequent analysis. The technical specifications of the pelletizing machine are presented in Table 4.

**Table 4.** Technical and operational specifications of the pellet machine.

| Specification                                                 | Measurement Unit | Parameters    |
|---------------------------------------------------------------|------------------|---------------|
| Electric motor rated power                                    | kW               | 7.50          |
| Electric motor supply voltage                                 | V                | 380           |
| Motor rotational speed                                        | rpm              | 1753          |
| Rotational speed of the shaft with rollers                    | rpm              | 320           |
| Number of rollers                                             | -                | 2             |
| Diameter of the press rollers                                 | mm               | 100           |
| Width of the press rollers                                    | mm               | 50            |
| Dimensions of the grooves on the rollers<br>(width × depth)   | mm               | 6 × 4         |
| Spacing of the grooves on the press rollers                   | mm               | 4             |
| Type of die                                                   | -                | Flat          |
| Die diameter                                                  | mm               | 200           |
| Thickness of the die                                          | mm               | 27            |
| Diameter of the holes in the die                              | mm               | 6             |
| Dimensions of the pellet machine (length ×<br>width × height) | cm               | 125 × 45 × 80 |
| Total mass of pelletizer                                      | kg               | 210           |
| Number of holes in the die                                    | -                | 234           |
| Capacity of the pellet machine                                | kg/h             | 250           |

#### 4.3. Pellet Dimensions

Diameter and length measurements were carried out with an analog caliper with an accuracy of 0.02 mm [27]. In this way, 90 pellets were selected for each treatment, and the average of the values obtained was determined.

#### 4.4. Specific and Bulk Density

The specific density of the pellets was determined from prior measurements of their diameter and length [26], along with the mass of randomly chosen samples. The mean of 90 measurements was calculated for each pellet formulation, with samples randomly selected. The calculation was carried out using Equation (1).

$$\rho_s = \frac{4 \cdot 10^6 \cdot m}{\pi \cdot d^2 \cdot l} \quad (1)$$

where,

$\rho_s$ : the specific density of the pellets, (kg/m<sup>3</sup>),

$m$ : the mass of a randomly chosen pellet sample (g),

$d$ : the average diameter of the pellets in the selected sample (mm), and

$l$ : the total length of the pellets in the selected sample (mm).

The bulk density of the pellets was calculated by measuring their mass and volume following the BS EN ISO 17828:2015 standard. The procedure involved filling a 5 L measurement container with the pellets, leveling the surface using a straight edge to remove any excess material, and then weighing the contents to compute the bulk density [68]. Bulk density was determined in triplicate for each pellet formulation [69].

#### 4.5. Chemical Composition

The chemical composition of the biomass, in terms of cellulose, hemicellulose, and lignin content, was determined using a fiber analyzer (Behrotest, CF6, Düsseldorf, Germany) to quantify the fibrous fractions [70]. The analysis was performed in triplicate [71]. For each determination, ground pellet samples were prepared according to the respective treatment. Extractives content was determined following the procedure outlined in NREL TP-510-42619.

#### 4.6. Moisture Content

The moisture content (MC) of the samples was determined using a gravimetric method, following the guidelines outlined in ISO 18134-3:2015 standard [72]. A sample weighing 1 g was dried in an oven set at 105 °C, and after 24 h, its mass was assumed to be stabilized. The loss in mass during drying was used to calculate the moisture content. Five replicate measurements were performed for each sample.

#### 4.7. Ash Content

To determine pellet ash content (AC), the procedure follows the method outlined in the ISO 18122:2015 standard [73]. The process involves completely combusting the sample in a furnace set at 550 °C until white ash is produced. A furnace (JPINGLOBAL, PCDIG7927, Mexico City, Mexico) was used, and porcelain crucibles containing the samples were heated until the ash formed. The mean and standard deviation were calculated based on five replicates for each treatment.

#### 4.8. Volatile Material

The measurement of the volatile content (VM) was performed by heating the biomass at 900 °C for 7 min, following the guidelines outlined in the defined standard [74]. A furnace (Carbolite Gero, VMF, Hope, Derbyshire, UK) was used, and the samples, placed in chromium-nickel crucibles, were heated until devolatilization occurred. The volatile matter percentage is determined by subtracting the mass loss caused by moisture evaporation from the total mass loss of the sample. This allows for the calculation of the volatile material rate on a dry basis. Each measurement was replicated five times.

#### 4.9. Fixed Carbon

The fixed carbon (FC) content was indirectly measured using Equation (2):

$$FC = 100\% - (MC + AC + VM) \quad (2)$$

#### 4.10. Ultimate Analysis

The contents of C, H, O, N, and S were measured by using a micro elemental analyzer (Velp Scientifica, EMA 502, Usmate Velate, Monza and Brianza, Italy). The sample quantities were measured using a microbalance (AND, BM-20, Tokyo, Japan). All results were expressed on a dry basis, and analytical procedures were replicated three times [11].

#### 4.11. Higher Heating Value

The higher heating value (HHV) was experimentally determined by combusting pellet samples in a bomb calorimeter (IKA C6000) [75], with each treatment replicated three times. The lower heating value (LHV) was determined following the equation described by Alves et al. [76].

#### 4.12. Impact Resistance

The impact resistance was determined by dropping a 20 g sample of pellets four consecutive times from a height of 2 m onto a concrete floor [28]. The scattered particles were gathered and passed through a 2 mm screen. Twelve replicates per formulation were tested to determine the mean impact resistance [16]. The impact resistance was calculated as the percentage ratio of the mass of biomass pellets retained on the sieve to the initial mass of pellets subjected to the drop test.

#### 4.13. Macro-TGA Analysis

A macro-scale thermogravimetric analysis (macro-TGA) system, housed at Universidad del Valle, Colombia, was utilized to assess the combustion under controlled conditions. This system can determine the combustion performance and thermal degradation characteristics of pellets. The experimental setup comprised a vertical tube furnace with a 65 mm quartz reaction chamber. A high-precision electronic balance, interfaced with a data acquisition system, continuously monitored the real-time mass loss of the sample as a function of temperature. Approximately 1 g of pellets from each biomass treatment was loaded into an alumina crucible, which was subsequently positioned on a refractory brick support and elevated into the furnace's reaction zone. The furnace temperature profile was programmed to increase at a controlled heating rate of 10 °C/min, reaching a final setpoint of 800 °C under air atmosphere. A blank run was performed using an empty-tared crucible, and the baseline drift was subtracted from all experimental measurements to ensure data accuracy and eliminate systematic deviations. Macro-TGA provides valuable insights into the combustion behavior of pellets, allowing the determination of key parameters such as ignition temperature ( $T_i$ ), burnout temperature ( $T_b$ ), the temperature at which maximum mass loss occurs ( $T_p$ ), maximum mass loss rate ( $DTG_{max}$ ), and mean mass loss rate ( $DTG_{mean}$ ). Additionally, indices such as the flammability index ( $FI$ ) and the comprehensive combustion index ( $CCI$ ) can be calculated to provide a deeper evaluation of the combustion performance for the samples [30] from the Equations (3) and (4):

$$FI = \frac{DTG_{max}}{T_i T_p} \quad (3)$$

$$CCI = \frac{DTG_{max} DTG_{mean}}{T_i^2 T_p} \quad (4)$$

#### 4.14. Pellet Quality Assessment

The quality assessment of pellets produced from RH, corncob, and their blends was conducted based on the value ranges specified for commercial-grade non-woody biomass according to ISO 17225-6:2021 [43].

#### 4.15. Statistical Analysis

A completely randomized single-factor categorical design was implemented with five treatments (five pellet formulations) and varying numbers of replicates, as the laboratory methods used for property determination follow specific protocols [22]. Before the analysis of variance (ANOVA), the Kolmogorov–Smirnov test (non-parametric, 5% significance level) was applied to verify the normality of residuals, the Breusch–Pagan test (5% significance level) was used to assess the homogeneity of variance, and the Runs test (5% significance level) was employed to confirm the independence of residuals, utilizing the software RStudio version 4.3.2, when ANOVA detected significant differences among treatments, means were compared using Tukey (HSD) test at a 5% significance level.

## 5. Conclusions

In this study, pellets were produced from RH, corncob, and their binary blends, utilizing residues sourced from the department of Sucre, Colombia. The carbon and hydrogen contents proved fundamental to the energy value of the biomass pellets, while high ash content had a markedly negative effect on fuel quality by reducing energy density. Understanding these relationships is essential for optimizing pellet formulations for thermochemical applications. The inclusion of corncob in blends with RH enabled effective modulation of ash content, resulting in class B pellets for the CC70:RH30 treatment. This

highlights the advantage of co-pelletizing agro-industrial residues with contrasting intrinsic characteristics, such as ash content. However, CC70:RH30 exhibited a lower average bulk density compared with CC30:RH70 and RH100, indicating that the physical durability of pellets is also influenced by the proportion of lignin-rich RH. Compared with single-residue pellets (CC100 and RH100), CC70:RH30 showed a lower ignition temperature and intermediate burnout behavior, while maintaining favorable flammability and comprehensive combustion indices. In terms of combustion indices, RH100 displayed the highest ignition resistance but also the lowest overall combustion reactivity, whereas CC100 was characterized by rapid ignition. The intermediate blends (particularly CC70:RH30) balanced these opposing characteristics, achieving a suitable trade-off between ignition, burnout, and ash modulation. These results confirm that co-pelletization of RH and corncob can effectively optimize combustion behavior and enhance thermal conversion performance while mitigating the limitations associated with using each residue independently. Overall, producing pellets from agro-industrial blends emerges as a viable strategy for generating solid biofuels of commercial quality, particularly in regions with high levels of agricultural waste generation. The integration of biomass sources ensures greater reliability for continuous solid biofuel supply chains, which is critical for scaling up and provides confidence to potential investors. Future studies should further refine sustainable pelletization strategies by considering the availability of residues, chemical composition, and intrinsic biomass properties specific to each geographical area. Additionally, incorporating assessments of mechanical durability, pretreatment energy balance, and ash fusibility would provide a more comprehensive evaluation of the suitability of blended agro-industrial residue pellets for large-scale thermochemical applications.

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## References

1. Dao, C.N.; Salam, A.; Kim Oanh, N.T.; Tabil, L.G. Effects of Length-to-Diameter Ratio, Pinewood Sawdust, and Sodium Lignosulfonate on Quality of Rice Straw Pellets Produced via a Flat Die Pellet Mill. *Renew. Energy* **2022**, *181*, 1140–1154. [[CrossRef](#)]
2. Ribun, V.; Boichenko, S.; Kale, U. Advances in Gas-to-Liquid Technology for Environmentally Friendly Fuel Synthesis: Analytical Review of World Achievements. *Energy Rep.* **2023**, *9*, 5500–5508. [[CrossRef](#)]

3. Sarker, T.R.; Borugadda, V.B.; Meda, V.; Dalai, A.K. Optimization of Pelletization Process Conditions and Binder Concentration for Production of Fuel Pellets from Oat Hull and Quality Evaluation. *Biomass Bioenergy* **2023**, *174*, 106825. [\[CrossRef\]](#)
4. Gargiulo, V.; Di Natale, F.; Alfe, M. From Agricultural Wastes to Advanced Materials for Environmental Applications: Rice Husk-Derived Adsorbents for Heavy Metals Removal from Wastewater. *J. Environ. Chem. Eng.* **2024**, *12*, 113497. [\[CrossRef\]](#)
5. Chen, R.; Congress, S.S.C.; Cai, G.; Duan, W.; Liu, S. Sustainable Utilization of Biomass Waste-Rice Husk Ash as a New Solidified Material of Soil in Geotechnical Engineering: A Review. *Constr. Build. Mater.* **2021**, *292*, 123219. [\[CrossRef\]](#)
6. Okeke, F.O.; Ahmed, A.; Imam, A.; Hassanin, H. A Review of Corncob-Based Building Materials as a Sustainable Solution for the Building and Construction Industry. *Hybrid. Adv.* **2024**, *6*, 100269. [\[CrossRef\]](#)
7. Nahak, B.K.; Preetam, S.; Sharma, D.; Shukla, S.K.; Syväjärvi, M.; Toncu, D.C.; Tiwari, A. Advancements in Net-Zero Pertinency of Lignocellulosic Biomass for Climate Neutral Energy Production. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112393. [\[CrossRef\]](#)
8. Anyaoha, K.E. Synergistic Perspective on Biomass Co-Utilization in Thermo-Chemical Processes. *Bioresour. Technol. Rep.* **2022**, *18*, 101043. [\[CrossRef\]](#)
9. Guo, F.; Chen, J.; He, Y.; Gardy, J.; Sun, Y.; Jiang, J.; Jiang, X. Upgrading Agro-Pellets by Torrefaction and Co-Pelletization Process Using Food Waste as a Pellet Binder. *Renew. Energy* **2022**, *191*, 213–224. [\[CrossRef\]](#)
10. Cui, X.; Yang, J.; Wang, Z.; Shi, X. Better Use of Bioenergy: A Critical Review of Co-Pelletizing for Biofuel Manufacturing. *Carbon Capture Sci. Technol.* **2021**, *1*, 100005. [\[CrossRef\]](#)
11. Setter, C.; Borges, F.A.; Cardoso, C.R.; Mendes, R.F.; Oliveira, T.J.P. Energy Quality of Pellets Produced from Coffee Residue: Characterization of the Products Obtained via Slow Pyrolysis. *Ind. Crops Prod.* **2020**, *154*, 112731. [\[CrossRef\]](#)
12. Pajampa, K.; Laloona, K.; Suksri, A.; Phadungton, S.; Ratpukdi, T.; Posom, J.; Wongwuttanasatian, T. A Way towards Zero-Waste Campaign and Sustainability in Sugar Industries; Filter Cake Valorisation as Energy Pellets. *Ain Shams Eng. J.* **2024**, *15*, 102459. [\[CrossRef\]](#)
13. García, R.; González-Vázquez, M.P.; Rubiera, F.; Pevida, C.; Gil, M.V. Co-Pelletization of Pine Sawdust and Refused Derived Fuel (RDF) to High-Quality Waste-Derived Pellets. *J. Clean. Prod.* **2021**, *328*, 129635. [\[CrossRef\]](#)
14. Ibitoye, S.E.; Jen, T.C.; Mahamood, R.M.; Akinlabi, E.T. Densification of Agro-Residues for Sustainable Energy Generation: An Overview. *Bioresour. Bioprocess.* **2021**, *8*, 75. [\[CrossRef\]](#)
15. Yılmaz, H.; Çanakçı, M.; Topakçı, M.; Karayel, D.; Yiğit, M.; Ortaçşme, D. In-Situ Pelletization of Campus Biomass Residues: Case Study for Akdeniz University. *Renew. Energy* **2023**, *212*, 972–983. [\[CrossRef\]](#)
16. Sarker, T.R.; Azargohar, R.; Dalai, A.K.; Meda, V. Characteristics of Torrefied Fuel Pellets Obtained from Co-Pelletization of Agriculture Residues with Pyrolysis Oil. *Biomass Bioenergy* **2021**, *150*, 106139. [\[CrossRef\]](#)
17. Stachowicz, P.; Stolarski, M.J. Pellets from Mixtures of Short Rotation Coppice with Forest-Derived Biomass: Production Costs and Energy Intensity. *Renew. Energy* **2024**, *225*, 120250. [\[CrossRef\]](#)
18. Joka Yildiz, M.; Cwalina, P.; Obidziński, S. A Comprehensive Study of Buckwheat Husk Co-Pelletization for Utilization via Combustion. *Biomass Convers. Biorefin.* **2024**, *14*, 27925–27942. [\[CrossRef\]](#)
19. de Almeida Moreira, B.R.; Barbosa Júnior, M.R.; de Brito Filho, A.L.; da Silva, R.P. Production of High-Quality Biogenic Fuels by Co-Pelletization of Sugarcane Bagasse with Pinewood Sawdust and Peanut Shell. *Biomass Convers. Biorefin.* **2024**, *14*, 6797–6820. [\[CrossRef\]](#)
20. Brand, M.A.; Mariano Rodrigues, T.; Peretti da Silva, J.; de Oliveira, J. Recovery of Agricultural and Wood Wastes: The Effect of Biomass Blends on the Quality of Pellets. *Fuel* **2021**, *284*, 118881. [\[CrossRef\]](#)
21. Iglesias Canabal, A.; Proupín Castiñeiras, J.; Rodríguez Añón, J.A.; Eimil Fraga, C.; Rodríguez Soalleiro, R. Elemental Composition of Raw and Torrefied Pellets Made from Pine and Pine-Eucalyptus Blends. *Biomass Bioenergy* **2023**, *177*, 106951. [\[CrossRef\]](#)
22. da Silva, S.B.; Arantes, M.D.C.; de Andrade, J.K.B.; Andrade, C.R.; de Cassia Oliveira Carneiro, A.; de Paula Protásio, T. Influence of Physical and Chemical Compositions on the Properties and Energy Use of Lignocellulosic Biomass Pellets in Brazil. *Renew. Energy* **2020**, *147*, 1870–1879. [\[CrossRef\]](#)
23. Vitoussia, T.; Leyssens, G.; Trouvé, G.; Brillard, A.; Kemajou, A.; Njeugna, E.; Brilhac, J.F. Analysis of the Combustion of Pellets Made with Three Cameroonian Biomass in a Domestic Pellet Stove. *Fuel* **2020**, *276*, 118105. [\[CrossRef\]](#)
24. Hossain, T.; Jones, D.S.; Godfrey, E.; Saloni, D.; Sharara, M.; Hartley, D.S. Characterizing Value-Added Pellets Obtained from Blends of Miscanthus, Corn Stover, and Switchgrass. *Renew. Energy* **2024**, *227*, 120494. [\[CrossRef\]](#)
25. Ríos-Badrán, I.M.; Luzardo-Ocampo, I.; García-Trejo, J.F.; Santos-Cruz, J.; Gutiérrez-Antonio, C. Production and Characterization of Fuel Pellets from Rice Husk and Wheat Straw. *Renew. Energy* **2020**, *145*, 500–507. [\[CrossRef\]](#)
26. Zawislak, K.; Sobczak, P.; Kraszkiewicz, A.; Niedziółka, I.; Parafiniuk, S.; Kuna-Broniowska, I.; Tanaś, W.; Żukiewicz-Sobczak, W.; Obidziński, S. The Use of Lignocellulosic Waste in the Production of Pellets for Energy Purposes. *Renew. Energy* **2020**, *145*, 997–1003. [\[CrossRef\]](#)
27. Kamga, P.L.W.; Vitoussia, T.; Bissoué, A.N.; Nguimbous, E.N.; Dieudjio, D.N.; Bot, B.V.; Njeugna, E. Physical and Energetic Characteristics of Pellets Produced from Movingui Sawdust, Corn Spathe, and Coconut Shells. *Energy Rep.* **2024**, *11*, 1291–1301. [\[CrossRef\]](#)

28. Kumar, P.; Subbarao, P.M.V.; Kala, L.; Vijay, V.K. Influence of Physical, Mechanical, and Thermal Properties of Biomass Pellets from Agriculture Residue: Pearl Millet Cob and Mix. *Bioresour. Technol. Rep.* **2022**, *20*, 101278. [\[CrossRef\]](#)
29. Solís, A.; Rocha, S.; König, M.; Adam, R.; Garcés, H.O.; Candia, O.; Muñoz, R.; Azócar, L. Preliminary Assessment of Hazelnut Shell Biomass as a Raw Material for Pellet Production. *Fuel* **2023**, *333*, 126517. [\[CrossRef\]](#)
30. Nie, Y.; Song, X.; Shan, M.; Yang, X. Effect of Pelletization on Biomass Thermal Degradation in Combustion: A Case Study of Peanut Shell and Wood Sawdust Using Macro-TGA. *Energy Built Environ.* **2024**; *in press*. [\[CrossRef\]](#)
31. Brand, M.A.; Jacinto, R.C. Apple Pruning Residues: Potential for Burning in Boiler Systems and Pellet Production. *Renew. Energy* **2020**, *152*, 458–466. [\[CrossRef\]](#)
32. He, H.; Wu, K.; Wang, Y.; Sun, Y.; Wu, J. Co-Pelleting of Biomass Feedstock: Effects of Blend Types and Ratios on Mechanical Behavior and Physical Properties. *Renew. Energy* **2025**, *244*, 122578. [\[CrossRef\]](#)
33. Nyashina, G.S.; Dorokhov, V.V.; Shvedov, D.K.; Strizhak, P.A. Effects of the Type and Proportion of a Binder on the Quality and Combustion of Fuel Pellets. *Biomass Bioenergy* **2025**, *199*, 107934. [\[CrossRef\]](#)
34. Rajput, S.P.; Jadhav, S.V.; Thorat, B.N. Methods to Improve Properties of Fuel Pellets Obtained from Different Biomass Sources: Effect of Biomass Blends and Binders. *Fuel Process. Technol.* **2020**, *199*, 106255. [\[CrossRef\]](#)
35. Loaiza, S.; Verchot, L.; Valencia, D.; Guzmán, P.; Amezquita, N.; Garcés, G.; Puentes, O.; Trujillo, C.; Chirinda, N.; Pittelkow, C.M. Evaluating Greenhouse Gas Mitigation through Alternate Wetting and Drying Irrigation in Colombian Rice Production. *Agric. Ecosyst. Environ.* **2024**, *360*, 108787. [\[CrossRef\]](#)
36. Ordoñez, L.; Vallejo, E.; Amariles, D.; Mesa, J.; Esquivel, A.; Llanos-Herrera, L.; Prager, S.D.; Segura, C.; Valencia, J.J.; Duarte, C.J.; et al. Applying Agrocimatic Seasonal Forecasts to Improve Rainfed Maize Agronomic Management in Colombia. *Clim. Serv.* **2022**, *28*, 100333. [\[CrossRef\]](#)
37. Arregocés, H.A.; Gómez, D.; Castellanos, M.L. Annual and Monthly Precipitation Trends: An Indicator of Climate Change in the Caribbean Region of Colombia. *Case Stud. Chem. Environ. Eng.* **2024**, *10*, 100834. [\[CrossRef\]](#)
38. Ministerio de Agricultura y Desarrollo Rural Reporte de Estadísticas de Producción Agrícola En Colombia. Available online: <https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=1> (accessed on 15 May 2024).
39. Sagastume Gutiérrez, A.; Mendoza Fandiño, J.M.; Cabello Eras, J.J.; Sofan German, S.J. Potential of Livestock Manure and Agricultural Wastes to Mitigate the Use of Firewood for Cooking in Rural Areas. The Case of the Department of Córdoba (Colombia). *Dev. Eng.* **2022**, *7*, 100093. [\[CrossRef\]](#)
40. Dias, F.d.S.; Meira, L.A.; Carneiro, C.N.; dos Santos, L.F.M.; Guimarães, L.B.; Coelho, N.M.M.; Coelho, L.M.; Alves, V.N. Lignocellulosic Materials as Adsorbents in Solid Phase Extraction for Trace Elements Preconcentration. *TrAC-Trends Anal. Chem.* **2023**, *158*, 116891. [\[CrossRef\]](#)
41. Gani, A.; Adisalamun; Arkan D, M.R.; Suhendrayatna; Reza, M.; Erdiwansyah; Saiful; Desvita, H. Proximate and Ultimate Analysis of Corn Cob Biomass Waste as Raw Material for Biocoke Fuel Production. *Case Stud. Chem. Environ. Eng.* **2023**, *8*, 100525. [\[CrossRef\]](#)
42. Noh, Y.H.; Lee, D.G.; Park, J.H.; Song, G.S.; Seung Kim, J.; Park, S.J.; Won Choi, J.; Ho Song, K.; Choi, Y.C.; Lee, Y.J. Ashless Herbaceous Biomass for Slagging and Fouling Reduction in Solid-Fuel Boiler: Combustion and Ash Fusion Characterizations. *Fuel* **2025**, *379*, 132957. [\[CrossRef\]](#)
43. ISO 17225-6; Solid Biofuels-Fuel Specifications and Classes-Part 6: Graded Non-Woody Pellets. ISO: Geneva, Switzerland, 2021.
44. Berghel, J.; Ståhl, M.; Frodeson, S.; Pichler, W.; Weigl-Kuska, M. A Comparison of Relevant Data and Results from Single Pellet Press Research Is Mission Impossible: A Review. *Bioresour. Technol. Rep.* **2022**, *18*, 101054. [\[CrossRef\]](#)
45. Szyszlak-Bargłowicz, J.; Słowik, T.; Zajac, G.; Blicharz-Kania, A.; Zdybel, B.; Andrejko, D.; Obidziński, S. Energy Parameters of Miscanthus Biomass Pellets Supplemented with Copra Meal in Terms of Energy Consumption during the Pressure Agglomeration Process. *Energies* **2021**, *14*, 4167. [\[CrossRef\]](#)
46. Miranda, M.T.; Sepúlveda, F.J.; Arranz, J.I.; Montero, I.; Rojas, C.V. Analysis of Pelletizing from Corn Cob Waste. *J. Environ. Manag.* **2018**, *228*, 303–311. [\[CrossRef\]](#)
47. Chen, C.; Yang, R.; Wang, X.; Qu, B.; Zhang, M.; Ji, G.; Li, A. Effect of In-Situ Torrefaction and Densification on the Properties of Pellets from Rice Husk and Rice Straw. *Chemosphere* **2022**, *289*, 133009. [\[CrossRef\]](#)
48. García, R.; Pizarro, C.; Lavín, A.G.; Bueno, J.L. Characterization of Spanish Biomass Wastes for Energy Use. *Bioresour. Technol.* **2012**, *103*, 249–258. [\[CrossRef\]](#)
49. Sykorova, V.; Jezerska, L.; Sassmanova, V.; Honus, S.; Peikertova, P.; Kielar, J.; Zidek, M. Biomass Pellets with Organic Binders—Before and after Torrefaction. *Renew. Energy* **2024**, *221*, 119771. [\[CrossRef\]](#)
50. Racero-Galaraga, D.; Rhenals-Julio, J.D.; Sofan-German, S.; Mendoza, J.M.; Bula-Silvera, A. Proximate Analysis in Biomass: Standards, Applications and Key Characteristics. *Results Chem.* **2024**, *12*, 101886. [\[CrossRef\]](#)
51. Aliyu, A.; Lee, J.G.M.; Harvey, A.P. Microalgae for Biofuels: A Review of Thermochemical Conversion Processes and Associated Opportunities and Challenges. *Bioresour. Technol. Rep.* **2021**, *15*, 100694. [\[CrossRef\]](#)

52. Cao, Y.; Bai, Y.; Du, J. Co-Gasification of Rice Husk and Woody Biomass Blends in a CFB System: A Modeling Approach. *Renew. Energy* **2022**, *188*, 849–858. [\[CrossRef\]](#)
53. Awais, M.; Omar, M.M.; Munir, A.; Li, W.; Ajmal, M.; Hussain, S.; Ahmad, S.A.; Ali, A. Co-Gasification of Different Biomass Feedstock in a Pilot-Scale (24 KWe) Downdraft Gasifier: An Experimental Approach. *Energy* **2022**, *238*, 121821. [\[CrossRef\]](#)
54. Mularski, J.; Li, J. A Review on Biomass Ignition: Fundamental Characteristics, Measurements, and Predictions. *Fuel* **2023**, *340*, 127526. [\[CrossRef\]](#)
55. Pahla, G.; Mamvura, T.A.; Ntuli, F.; Muzenda, E. Energy Densification of Animal Waste Lignocellulose Biomass and Raw Biomass. *S. Afr. J. Chem. Eng.* **2017**, *24*, 168–175. [\[CrossRef\]](#)
56. Zakaria, M.R.; Ahmad Farid, M.A.; Andou, Y.; Ramli, I.; Hassan, M.A. Production of Biochar and Activated Carbon from Oil Palm Biomass: Current Status, Prospects, and Challenges. *Ind. Crops Prod.* **2023**, *199*, 116767. [\[CrossRef\]](#)
57. Yaka, H.; Insel, M.A.; Yucel, O.; Sadikoglu, H. A Comparison of Machine Learning Algorithms for Estimation of Higher Heating Values of Biomass and Fossil Fuels from Ultimate Analysis. *Fuel* **2022**, *320*, 123971. [\[CrossRef\]](#)
58. Islam, M.R.; Tarikuzzaman, M.; Lynam, J.G. Hydrothermal Carbonization for Extracting Lignin from Agricultural Biomass Rice Husks and Cotton Gin Trash. *Bioresour. Technol. Rep.* **2025**, *30*, 102144. [\[CrossRef\]](#)
59. Volli, V.; Gollakota, A.R.K.; Shu, C.-M. Comparative Studies on Thermochemical Behavior and Kinetics of Lignocellulosic Biomass Residues Using TG-FTIR and Py-GC/MS. *Sci. Total Environ.* **2021**, *792*, 148392. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Cai, J.; He, Y.; Yu, X.; Banks, S.W.; Yang, Y.; Zhang, X.; Yu, Y.; Liu, R.; Bridgwater, A.V. Review of Physicochemical Properties and Analytical Characterization of Lignocellulosic Biomass. *Renew. Sustain. Energy Rev.* **2017**, *76*, 309–322. [\[CrossRef\]](#)
61. Agar, D.A.; Rudolfsson, M.; Laverigne, S.; Melkior, T.; Da Silva Perez, D.; Dupont, C.; Campargue, M.; Kalén, G.; Larsson, S.H. Pelletizing Torrefied Biomass at Pilot-Scale—Quality and Implications for Co-Firing. *Renew. Energy* **2021**, *178*, 766–774. [\[CrossRef\]](#)
62. Draszewski, C.P.; Bragato, C.A.; Lachos-Perez, D.; Celante, D.; Frizzo, C.P.; Castilhos, F.; Tres, M.V.; Zabot, G.L.; Abaide, E.R.; Mayer, F.D. Subcritical Water Hydrolysis of Rice Husks Pretreated with Deep Eutectic Solvent for Enhance Fermentable Sugars Production. *J. Supercrit. Fluids* **2021**, *178*, 105355. [\[CrossRef\]](#)
63. Chen, C.; Qu, B.; Wang, W.; Wang, W.; Ji, G.; Li, A. Rice Husk and Rice Straw Torrefaction: Properties and Pyrolysis Kinetics of Raw and Torrefied Biomass. *Environ. Technol. Innov.* **2021**, *24*, 101872. [\[CrossRef\]](#)
64. Awosusi, A.A.; Ayeni, A.O.; Adeleke, R.; Daramola, M.O. Biocompositional and Thermodecompositional Analysis of South African Agro-Waste Corn cob and Husk towards Production of Biocommodities. *Asia-Pac. J. Chem. Eng.* **2017**, *12*, 960–968. [\[CrossRef\]](#)
65. Quintero-Naucil, M.; Salcedo-Mendoza, J.; Solarte-Toro, J.C.; Aristizábal-Marulanda, V. Assessment and Comparison of Thermochemical Pathways for the Rice Residues Valorization: Pyrolysis and Gasification. *Environ. Sci. Pollut. Res.* **2024**, *1–8*. [\[CrossRef\]](#)
66. Atay, O.A.; Ekinci, K. Characterization of Pellets Made from Rose Oil Processing Solid Wastes/Coal Powder/Pine Bark. *Renew. Energy* **2020**, *149*, 933–939. [\[CrossRef\]](#)
67. Guo, G.; Zhang, K.; Liu, C.; Xie, S.; Li, X.; Li, B.; Shu, J.; Niu, Y.; Zhu, H.; Ding, M.; et al. Comparative Investigation on Thermal Decomposition of Powdered and Pelletized Biomasses: Thermal Conversion Characteristics and Apparent Kinetics. *Bioresour. Technol.* **2020**, *301*, 122732. [\[CrossRef\]](#) [\[PubMed\]](#)
68. ISO 17828:2015; Solid Biofuels-Determination of Bulk Density. ISO: Geneva, Switzerland, 2015.
69. Agar, D.A.; Rudolfsson, M.; Kalén, G.; Campargue, M.; Da Silva Perez, D.; Larsson, S.H. A Systematic Study of Ring-Die Pellet Production from Forest and Agricultural Biomass. *Fuel Process. Technol.* **2018**, *180*, 47–55. [\[CrossRef\]](#)
70. Van Soest, P.J.; Robertson, J.B.; Lewis, B.A. Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition. *J. Dairy. Sci.* **1991**, *74*, 3583–3597. [\[CrossRef\]](#)
71. Lei, T.; Huang, H.; Tan, M.; Huang, Z.; Li, C.; Liu, P.; Zhou, X.; Zhang, X.; Huang, J.; Li, H. The Effect of Additives on the Co-Pelletization of Sewage Sludge and Extraction Residue on Combustion Behavior and off-Gas Emission Reduction. *Biomass Bioenergy* **2024**, *184*, 107181. [\[CrossRef\]](#)
72. ISO 18134-3:2015; Solid Biofuels-Determination of Moisture Content-Oven Dry Method-Part 3: Moisture in General Analysis Sample. ISO: Geneva, Switzerland, 2015.
73. ISO 18122:2015; Solid Biofuels-Determination of Ash Content. ISO: Geneva, Switzerland, 2015.
74. ISO-18123:2015; Solid Biofuels-Determination of the Content of Volatile Matter. ISO: Geneva, Switzerland, 2015.
75. Lee, K.-T.; Gabriela, S.; Chen, W.-H.; Ong, H.C.; Rajendran, S.; Tran, K.-Q. Co-Torrefaction and Synergistic Effect of Spent Coffee Grounds and Tea Waste for Sustainable Waste Remediation and Renewable Energy. *Renew. Energy* **2024**, *233*, 121181. [\[CrossRef\]](#)
76. Alves, J.L.F.; da Silva, J.C.G.; Mumbach, G.D.; Di Domenico, M.; Marangoni, C. Assessing the Potential of the Invasive Grass *Cenchrus Echinatus* for Bioenergy Production: A Study of Its Physicochemical Properties, Pyrolysis Kinetics and Thermodynamics. *Thermochim. Acta* **2023**, *724*, 179500. [\[CrossRef\]](#)

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