International Journal of Nature and Life Sciences

IJNLS

https://dergipark.org.tr/tr/pub/ijnls

e-ISSN: 2602-2397 https://doi.org/10.47947/ijnls.1843026

Research Article

The Pelletizability of Tea Waste and the Effect of Moisture Content and Pellet Diameter on Pellet Properties

Mehmet Akif Tanrıverdi [1], Bahadır Demirel [2*], Osman Mert Yaz [3]

[1] Erciyes University, Graduate School of Natural and Applied Sciences, Department of Biosystems Engineering, Kayseri, Türkiye; https://orcid.org/0009-0001-9223-4108

[2] Erciyes University, Faculty of Agriculture, Department of Biosystems Engineering, Kayseri, Türkiye; https://orcid.org/0000-0002-2650-1167

[3] Erciyes University, Faculty of Agriculture, Department of Biosystems Engineering, Kayseri, Türkiye; https://orcid.org/0009-0003-3367-6656

*** Corresponding author:** bahdem@erciyes.edu.tr

Received: December 16, 2025

Accepted: December 21, 2025

Online Published: December 22, 2025

Citation: Tanrıverdi, M.A., Demirel, B., Yaz, O.M., (2025). The pelletizability of tea waste and the effect of moisture content and pellet diameter on pellet properties. International Journal of Nature and Life Sciences, 9 (2), 142-155.

Abstract: In this study, the pelletability of tea waste, a by product of tea factories, was investigated, along with the effects of different moisture contents and pellet diameters on the physical and mechanical properties of the resulting pellets. The experiments were conducted using two different moisture levels (8–9% and 11–12%) and three different pellet diameters (6, 8, and 10 mm). The findings revealed that moisture content is one of the most important parameters determining pellet quality. Pellets produced at higher moisture content (11–12%) exhibited significantly better performance in terms of mechanical strength, impact resistance, and fracture resistance under pressure compared to pellets with lower moisture content. Under low moisture conditions, pellets became more brittle, and strength losses were particularly pronounced in larger pellets. When evaluating the effects of pellet diameter, it was determined that as the diameter decreased, the mechanical integrity and strength properties of the pellets increased. Pellets with a diameter of 6 mm yielded the highest quality values, while pellets with a diameter of 10 mm exhibited weaker properties, especially under low humidity conditions. It has been confirmed that moisture content and pellet diameter have significant effects on all parameters defining pellet quality. Correlation and PCA results showed that properties such as mechanical strength, impact resistance, compressive strength, and density changed together and that high moisture–small diameter combinations were associated with higher quality pellets. It can be stated that tea waste can be converted into a high-quality pellet fuel without the use of any binder under suitable conditions, and that a moisture content of 10–12% and a diameter range of 6–8 mm are particularly favorable for tea waste pellet production. These findings point to significant potential for the energy-based utilization of tea waste in regions with intensive tea production.

Keywords: Biomass energy; Moisture content; Pellet diameter; Pelletization; Tea waste.

1. Introduction

Due to the environmental impacts and limited reserves of fossil fuels, the shift toward renewable energy sources is steadily increasing. Biomass energy is considered a significant alternative in this field due to its sustainability and carbon neutrality (Mignogna et al., 2024). Türkiye holds an important position in global tea

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license

production; tea cultivation is carried out on approximately 759,000 decares of land, and around 20,000 tons of tea waste is generated annually in 45 factories affiliated with ÇAYKUR (Dok, 2014; Bilgin et al., 2016). However, most of this waste is incinerated or disposed of without being given any economic value (Ungureanu, 2018). Yet, converting tea factory waste into pellet fuel offers an attractive solution in terms of both waste management and renewable energy production (Dok, 2014; Bajwa et al., 2018). Since the moisture content of the pulp from tea production processes is generally below 15%, it is also a significant advantage that it is suitable for pelletization without requiring additional drying (Ungureanu, 2018; Yılmaz, 2018; Ribeiro and Junioar, 2023). Indeed, in their study, Bilgin et al. (2016) obtained pellets with a volume density of approximately 601 $kg.m^{-3}$ and 81% durability by directly pelletizing tea factory waste, thus demonstrating that tea waste can be evaluated as a robust biofuel pellet. Similarly, this study aimed to pelletize tea waste without any binding additives and to investigate the effects of different process conditions on pellet quality.

One of the most significant problems encountered in the direct use of raw biomass for energy purposes is its low bulk density, irregular particle shape, and high moisture content (Kaliyan and Morey, 2009; Stelte et al., 2012). These characteristics can lead to inefficiency in transportation and storage, as well as unstable combustion during burning. Pelletizing biomass is a widely used method to overcome these problems (Bajwa et al., 2018; Sarker et al., 2023). Pelletized biomass increases the volumetric density of the original raw material by several times, thereby improving transportation and storage efficiency, acquiring a homogeneous cylindrical form, and exhibiting more stable combustion performance (Gürdil, 2020; Demirel and Gürdil, 2022; Demirel, 2023). For example, it has been reported that pelletizing tea waste increases the bulk density of the product by ~5.7 times and the stack density by ~3 times compared to the raw material density (Bilgin et al., 2016).

When examining the quality standards for pellet fuels, it is seen that criteria such as mechanical strength, moisture and ash content, and size are critical; indeed, the European standard EN 14961-2 (2011) specifies that good-quality pellets must have a bulk density of at least 600 $kg.m^{-3}$, mechanical strength above 97%, and moisture content below 10%. The fundamental physical properties that determine pellet quality include pellet density, bulk density, mechanical strength, impact resistance, and pressure resistance. These properties are largely dependent on pelletizing process parameters and raw material characteristics. The literature indicates that raw material particle size, moisture content, die temperature, and pressure are decisive factors in pellet density and strength (Kaliyan and Morey, 2009; Stelte et al., 2012; Mostafa et al., 2019). It is known that smaller particle sizes provide denser and stronger pellets, while an appropriate moisture level facilitates fiber bonding (Kaliyan and Morey, 2009; Filbakk et al., 2011; Miranda et al., 2015).

Moisture content is a critical factor that affects the fluidity of natural adhesives such as lignin and the bonding of fibers during pellet formation. Sufficient moisture, together with pressure and heat, acts as a binding agent within the pellet, increasing its density and durability (Kaliyan and Morey, 2009; Mostafa et al., 2019; Picchio et al., 2020; Li et al., 2022). On the other hand, excessively low moisture (<8%) causes pellets to be brittle and fragile, while very high moisture levels (>~15–20%) can reduce pellet quality and cause deterioration during storage (Li et al., 2022; He et al., 2024; Mortadha et al., 2025). Indeed, in a review, Ungureanu et al. (2018) emphasized that the optimal moisture content in raw materials is around 10%; pellets produced with very low moisture content (5%) are fragile and produce excessive dust, while pellets with moisture content above 20% lose their integrity. Similarly, other studies have reported that a moisture content of approximately 10–15% maximizes pellet hardness and strength (Serrano et al., 2011).

Pellet diameter (die hole diameter) is also an important process variable that can affect pellet quality. In industry, domestic biofuel pellets are generally produced with a diameter of 6–8 mm, while industrial pellets are produced with a diameter of 10–12 mm. As pellet diameter increases, the specific pressure applied by the pelletizing press and the distribution of the heat generated change. These changes can lead to complex effects on pellet density and mechanical strength. The literature contains findings that larger die diameters generally increase pellet bulk density but can reduce mechanical strength. For example, Tumuluru (2018), in his study on the pelletization of high-moisture woody biomass, reported that pellets produced with a 10 mm die had higher densities than those produced with an 8 mm die, but pellet strength decreased as the diameter increased. Similarly, Kuranc et al. (2020) reported in their study on wood pellets that pellets with a diameter of 8 mm exhibited lower durability than those with a diameter of 6 mm, and that more breakage and dusting was observed in 8 mm pellets during vibratory transport. Furthermore, it has been observed that durability decreases as the diameter increases in sunflower seed cake pellets

(Lunguleasa et al., 2024). While this suggests that pellet geometry may play a role in durability, the authors of the study noted that material composition is also influential and that controlled studies using the same raw material are needed to clarify the diameter-durability relationship. On the other hand, in their study comparing 7 and 10 mm diameters of pellets produced from green tea waste using the pressing method, Thanphrom et al. (2022) measured the durability of larger diameter (10 mm) pellets as 95.6% and found it to be higher than that of 7 mm pellets (~90.2%). Such differing results indicate that the effect of pellet diameter may vary depending on the interaction between the pelletization method, raw material properties, and process conditions. Therefore, it is important to evaluate both moisture and diameter factors together for a specific biomass such as tea waste.

2. Materials and Methods

2.1. Materials

The tea waste used as raw material in this study was obtained from tea houses and municipal cafes affiliated with the Melikgazi Municipality in Kayseri Province. The collected tea waste was spread on a concrete floor in an open area to a thickness of approximately 4–5 cm and dried. The moisture content was reduced to a range of 11–12% prior to the experiment to obtain the basic raw material. For low-moisture experiments, a portion of the dry residue was kept in an air dryer to reduce the moisture content to approximately 8–9%. The material from both moisture groups was kept in closed bags for at least 24 hours to obtain a homogeneous mixture before pelletization. Before proceeding to pelletization, representative samples were taken and dried in an oven at 105 °C to determine their exact moisture content.

The raw material underwent mechanical size reduction prior to pelletization. The dried tea residue was ground using a laboratory-type hammer mill. The particle size distribution of the ground material was checked by sieve analysis; the average particle diameter was found to be approximately 1–2.8 mm. This particle size is within the range of <1–2 mm, which is considered suitable for pelletization in the literature, and it is known that small particles contribute positively to pellet strength (Kaliyan and Morey, 2009).

A laboratory-scale flat die pellet machine was used for pellet production. The machine is a system driven by a 3 kW electric motor and equipped with interchangeable steel die discs. Three different dies with diameters of 6, 8, and 10 mm were used in the experiments to investigate the effect of pellet diameter. Each die was mounted on the machine with appropriate compression cylinders and settings, and separate trials were conducted. The machine consists of a flat die in a horizontal arrangement and two rotating cylinders on top; the rotation speed of the cylinders was kept constant at ~80–100 rpm. Raw material feeding was performed in a controlled manner from a gravity-fed hopper; sampling commenced after a stable pellet flow was achieved for each mold when the machine was fed. After the machine reached stable operation for each moisture and mold combination, approximately 6 kg of pellets were produced, and samples were taken from the pellets following the initial discard. Thus, a total of 6 groups of pellets were obtained from 2 different moisture × 3 different diameter combinations. To ensure that the temperature formed in the machine mold during pelletizing was similar in all tests, short pauses were made when necessary to prevent the mold from overheating (the mold temperature was maintained between 70–90 °C).

The pellets produced were left to rest for 3 days under room conditions (20–25 °C, 50–60% relative humidity) before testing to allow their quality characteristics to stabilize. During this period, the pellets were stored in airtight containers with closed lids and removed to the external environment a few hours before testing to allow them to reach equilibrium moisture content. Bilgin et al. (2016) similarly allowed the pellets to rest for 7 days before testing to ensure equilibrium moisture content.

2.2. Methods

The bulk density of the pellets was determined in accordance with the EN 16127 standard. The diameter and length of 10 pellets randomly selected from each group were measured using a digital caliper, and their individual masses were weighed on a scale with a precision of 0.001 g. The density of each pellet was calculated by dividing its mass by its volume and recorded in kg.m^{-3}. These individual density values were averaged for the same group to obtain the “particle density” result for that group.

The bulk density of the pellets when filling a volume was measured according to the EN 15103 standard. As defined in the standard, a 1 L cylindrical container was filled by freely pouring pellets from a height of approximately 30 cm. After the container was filled, the pellets overflowing on the surface were scraped off with a flat wooden trowel. The total mass of the pellets in the container was weighed, and the bulk density (kg.m^{-3}) was calculated as the ratio of the mass to the 1 L volume. This process was repeated three times for each group, and the average was taken.

To measure the mechanical strength of the pellets, a Tumbler test was performed in accordance with the EN 15210-1 standard. For each test group, the pellet sample was first passed through a sieve with a 3.15 mm mesh size to remove dust and fine particles. The 500±1g pellet sample remaining on the sieve was placed in a rotating drum device with a baffle and rotated at 50 rpm for 10 minutes. At the end of the time, the sample was removed from the drum and sieved again through a 3.15 mm sieve. The final mass of the intact pellets was measured. Mechanical strength (%) was calculated using the formula 100 x (final mass / initial mass) by comparing the masses before and after the test. This test was repeated three times for each group, and the average strength value was obtained.

The integrity ratios of the pellets against falling from a certain height (impact resistance percentage) were evaluated using a standard Shatter test procedure. For each group, 3 pellets were dropped freely onto a hard plate from a height of 1.85 meters (each pellet was dropped 4 times consecutively). The percentage of pellets remaining intact after the drop was calculated. In addition, the particle sizes formed after the pellets broke were observed in this test. As a result of the Shatter test, the impact resistance percentage was determined by the ratio of the number of pellets remaining intact to the initial total number. Three repetitions were performed for each group, and the average value was reported.

A universal testing machine was used to measure the fracture resistance of the pellets under pressure. Ten pellets randomly selected from each group were broken on a pressure test stand by applying a load perpendicular to their diameter. A single pellet was placed between the lower and upper plate planes of the testing device, and a uniaxial compressive force was applied. The maximum force value at the moment of pellet breakage was recorded by the software. This breaking load value was taken for each pellet, and the mean and standard deviation were calculated for the group. The pressure resistance results are presented in kN units.

A two-factor analysis of variance (ANOVA) was performed for all measurement data to test the effects of the factors “moisture content” (low/high) and “pellet diameter” (6, 8, and 10 mm). For effects found to be significant in the variance analysis, subgroup comparisons were made using the Tukey HSD test at a 95% confidence level. In addition, Pearson correlation coefficients were calculated between the measured quantitative parameters to create a correlation matrix. Finally, Principal Component Analysis (PCA) was applied to examine the relationships among the six variables (Raw material density, Pellet particle density, Bulk density, Durability, Impact resistance, Breaking strength).

3. Results

The material density of pellets, along with their bulk and individual densities, and fundamental quality characteristics such as mechanical strength, fragmentation resistance, and compressive strength; were measured for two different moisture levels (8–9% and 11–12%) and three different pellet diameters (6, 8, and 10 mm). The means and standard deviations for these values are presented in Table 1.

Table 1. Physical and mechanical properties of pellets at different moisture contents and pellet diameters (mean ± SD).

Moisture content (%)	Pellet diameter (mm)	Material density (kg·m^{-3})	Pellet density (kg·m^{-3})	Pellet bulk density (kg·m^{-3})	Tumbler durability (%)	Shatter resistance (%)	Compressive strength (kN)
8–9	6	344.98 ± 2.53^{c}	1051.77 ± 27.25^{a}	734.00 ± 11.47^{b}	89.15 ± 1.67^{b}	97.58 ± 0.59^{a}	0.670 ± 0.041^{b}
8–9	8	344.98 ± 2.53^{c}	914.53 ± 36.02^{b}	663.94 ± 6.76^{b}	77.37 ± 2.47^{b}	94.52 ± 0.98^{a}	0.374 ± 0.060^{b}
8–9	10	344.98 ± 2.53^{c}	900.96 ± 21.54^{b}	631.91 ± 2.36^{b}	68.31 ± 6.29^{b}	95.82 ± 1.89^{a}	0.531 ± 0.097^{b}
11–12	6	387.01 ± 0.62^{c}	1014.98 ± 2.42^{a}	713.82 ± 1.40^{a}	92.01 ± 0.66^{a}	95.94 ± 0.60^{a}	0.640 ± 0.026^{a}
11–12	8	392.74 ± 1.40^{b}	1022.50 ± 1.05^{b}	727.30 ± 2.14^{a}	93.13 ± 0.68^{a}	96.35 ± 0.13^{a}	0.697 ± 0.015^{a}
11–12	10	396.37 ± 0.88^{a}	1026.66 ± 1.09^{b}	738.25 ± 2.00^{a}	94.96 ± 0.60^{a}	97.72 ± 0.57^{a}	0.717 ± 0.025^{a}

* Values are presented as mean ± standard deviation (n = 3).

* Different letters within the same column indicate significant differences according to Tukey’s multiple comparison test ($p < 0.05$).

When examining Table 1, which contains the average values and standard deviations related to material density for different moisture content and pellet diameter combinations, these values are generally similar across all groups, at approximately 368.5 kg.m^{-3}. The interaction graph created to visualize the trends of this parameter according to experimental variables is shown in Figure 1a, allowing for the joint evaluation of moisture content and pellet diameter factors.

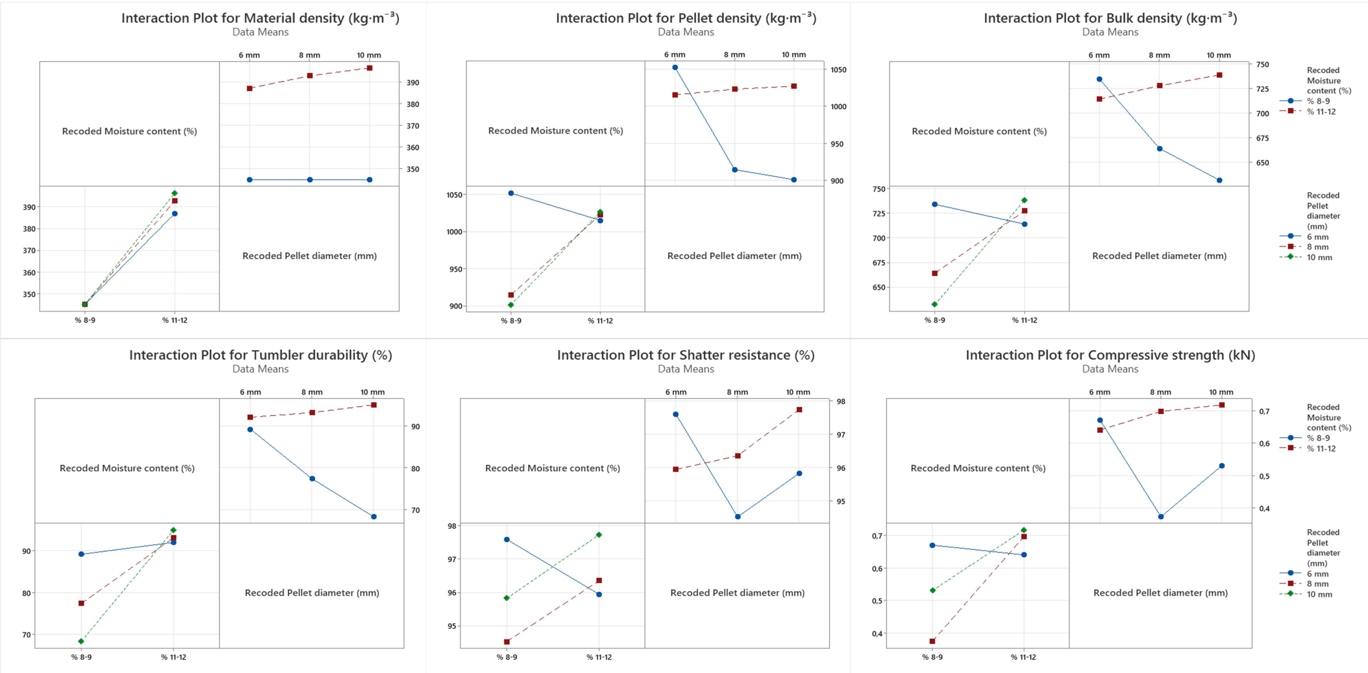

Figure 1. Interaction graphs showing the effects of different moisture content (%) and pellet diameter (mm) combinations on quality parameters. In order: (a) material density, (b) pellet density, (c) bulk density, (d) tumbler durability, (e) impact resistance, and (f) compression resistance.

As can be seen in the Figure 1a, a slight upward trend in material density is observed with increasing moisture content. However, this increase does not indicate a statistically significant change (p>0.05; Table 2). Similarly, neither pellet diameter nor the interaction of the two variables had a significant effect on material density. This indicates that the physical properties of the tea waste used remained constant within a certain range and were not greatly affected by production conditions in terms of density.

Table 2. Two-way ANOVA results (P-values) for pellet.

Property	Moisture content (P)	Pellet diameter (P)	Moisture × Diameter (P)
Material density (kg·m^{-3})	< 0.001	0.004	0.004
Pellet density (kg·m^{-3})	< 0.001	< 0.001	< 0.001
Bulk density (kg·m^{-3})	< 0.001	< 0.001	< 0.001
Tumbler durability (%)	< 0.001	0.001	< 0.001
Shatter resistance (%)	0.153	0.052	0.012
Compressive strength (kN)	< 0.001	0.005	< 0.001

* P-values were obtained from two-way ANOVA analyses considering moisture content, pellet diameter, and their interaction. Values in bold indicate statistically significant effects (P < 0.05).

In general, it was determined that the bulk densities of pellets obtained from tea waste ranged between 1100–1250 kg.m^{-3} (Table 1). The results of the two-way ANOVA showed that the “moisture content” factor had no statistically significant effect on bulk density (p > 0.05; Table 2). It was observed that the bulk densities of the low-moisture and high-moisture groups were similar. In contrast, it was found that the “pellet diameter" factor had a significant effect on bulk density ($p < 0.01$; Table 2). According to the results of the Tukey multiple comparison test, the average density of 10 mm diameter pellets (~1220 $kg.m^{-3}$) was found to be statistically significantly higher than other diameter groups ($p < 0.05$). No statistically significant difference was observed between the densities of pellets with diameters of 6 and 8 mm.

The interaction graph showing the change in piece density depending on moisture content and pellet diameter is presented in Figure 1b. This finding is consistent with studies in the literature reporting that larger mold diameters allow for the production of denser pellets under certain conditions (Tumuluru, 2018). It is thought that, especially when a 10 mm die diameter is used, the material remains in the die for a relatively longer time, exposing it to higher compression pressure, which may explain the increase in particle density.

When examining the results of the bulk density of the pellets, an inverse trend was observed compared to the piece density. 6 mm diameter pellets accommodated the most mass per unit volume and yielded the highest bulk density (~630 $kg.m^{-3}$), whereas 10 mm diameter pellets had the lowest bulk density (~560 $kg.m^{-3}$) (Table 1). According to the two-way ANOVA results, the effect of pellet diameter on bulk density is statistically significant ($p < 0.01$; Table 2). The Tukey multiple comparison test revealed that the bulk density of 6 mm diameter pellets was significantly higher than that of 8 and 10 mm diameter pellets ($p < 0.05$).

The interaction graph showing the change in bulk density depending on moisture content and pellet diameter is presented in Figure 1c. This is due to the fact that pellets with smaller diameters can be stacked more regularly in containers and fill the void volume more effectively. The effect of moisture content on bulk density was not found to be statistically significant, with the low and high moisture groups exhibiting similar bulk density values ($p > 0.05$; Table 2). At both moisture levels, bulk density values ranged from 550–650 $kg.m^{-3}$ for all diameters and were generally found to meet the threshold values specified in biofuel pellet standards (EN 14961-2, 2011).

The mechanical strength percentages of pellets according to the tumbler test are given in Table 1. Under low moisture (8–9%) production conditions, a significant decrease in mechanical strength was observed. Particularly in pellets with a diameter of 8 and 10 mm, samples with low moisture content showed a significant amount of breakage and wear after the tumbler test (Table 1). In contrast, pellets with high moisture content (11–12%) exhibited much higher strength values in all diameter groups.

Two-way ANOVA results revealed that both moisture content and pellet diameter had highly significant effects on mechanical durability ($p < 0.001$ for both factors; Table 2). When the effect of moisture was evaluated, it was determined that the average durability values were above 90% in the high-moisture groups and between 70–80% in the low-moisture groups (Table 1). The Türkiye multiple comparison test confirmed that the strength of high-moisture pellets was statistically significantly higher than that of low-moisture pellets ($p < 0.05$). This finding is consistent with the general acceptance that water plays a binding role in the pelletization process (Ungureanu et al., 2018). It is thought that sufficient moisture increases pellet integrity by fluidizing lignin and other natural polymers.

When examining the diameter effect, mechanical strength was found to increase as pellet diameter decreased. The highest mechanical strength values were obtained for pellets with a diameter of 6 mm (Table 1, Figure 1d). For example, mechanical strength values reached 95% levels for the combination of 6 mm diameter and high moisture, while these values fell below 70% for the combination of 10 mm diameter and low moisture. According to the Türkiye test results, the average strength of 6 mm diameter pellets was found to be statistically significantly higher than that of 8 mm and 10 mm diameter pellets ($p < 0.05$). No statistically significant difference was found between 8 mm and 10 mm diameter pellets (Table 2).

The integrity ratios (impact resistance percentage) of pellets when dropped from a specific height are presented in Table 1. In general, in line with the trends observed in the mechanical durability (Tumbler) test, it was determined that impact resistance is also affected by moisture content and pellet diameter (Figure 1e). Pellets produced at high moisture content (11–12%) were largely able to withstand a drop from a height of 1.85 m and exhibited integrity rates above 90% (Table 1). In contrast, low-moisture pellets (8–9%) showed increased breakage and cracking as a result of the drop, with survival rates falling below 80% in some groups. In particular, 10 mm diameter, low-moisture pellets showed the weakest performance in the Shatter test (75–80% survival).

According to the two-way ANOVA analysis, both moisture content and pellet diameter had statistically significant effects on impact resistance ($p < 0.01$; Table 2). The average impact resistance of high-moisture samples (92%) was significantly higher than that of low-moisture samples (82%). Similarly, the impact resistance of pellets with a diameter of 6 mm (~95%) was found to be statistically significantly higher compared to pellets with diameters of 8 mm (~88%) and 10 mm (~80%) ($p < 0.05$). These results are consistent with the mechanical strength values measured by the Tumbler test; pellets with high mechanical integrity were found to better maintain their integrity in the impact test.

For each group, the maximum load values (kN) during pellet breakage were measured and average values were calculated (Table 1). According to the results obtained, high-moisture pellets exhibited significantly higher breakage strength compared to low-moisture pellets. For example, the average breaking load of 6 mm diameter pellets produced with 11–12% moisture content was approximately 0.50 kN, while the breaking strength of equivalent pellets with 8–9% moisture content remained at approximately 0.35 kN (Figure 1f). Similarly, it was determined that high moisture groups exhibited 0.10–0.15 kN higher breaking resistance compared to low moisture groups across all pellet diameters.

In the two-way ANOVA analysis, $p < 0.001$ was found for the moisture content factor, confirming that the effect on breaking strength was statistically highly significant (Table 2). When the pellet diameter factor was evaluated, it was observed that the breaking strength values were similar between 6 and 8 mm diameter pellets (~0.45–0.50 kN), while they were slightly lower for 10 mm diameter pellets (~0.40 kN) (Table 1). However, the main effect of diameter was found to be at the threshold of statistical significance ($p \approx 0.07$; Table 2). This situation is thought to be related to the high variation observed in the 10 mm pellet group; the distribution within the group widened due to some 10 mm pellets breaking at relatively low loads.

According to the Tukey multiple comparison test results, there was no clear differentiation between pellet diameters in terms of fracture strength, but the general trend was determined to be that smaller diameter pellets could carry slightly higher fracture loads. This trend can be attributed to the more dense structure of smaller pellets and their lower likelihood of containing internal defects. However, the poor performance of 10 mm pellets in the fracture test is generally not very pronounced; only in low-moisture 10 mm samples were some pellets observed to fracture at very early loads (~0.2 kN). High-moisture 10 mm pellets, on the other hand, reached values above 0.45 kN, exhibiting similar mechanical strength to small-diameter pellets (Figure 1f).

3.1. Correlation analysis of physical and mechanical properties

The Pearson correlation coefficients between the measured physical and mechanical properties are shown in Figure 2. One of the most notable relationships is the strong positive correlation observed between pellet density and mechanical strength ($r = 0.86$). Similarly, a very strong positive relationship was determined between bulk density and mechanical strength ($r = 0.93$). There is a medium-high positive correlation between mechanical strength and fracture resistance under pressure ($r = 0.65$), indicating that pellets that are durable in the drum test are also more resistant to pressure loads. A strong positive relationship was also found between impact resistance and pressure resistance ($r = 0.76$). Furthermore, the positive correlation between pellet density and bulk density with both mechanical strength and pressure resistance indicates that denser and more compactable pellets generally exhibit higher mechanical performance. This finding is consistent with the literature indicating that a decrease in the void ratio within the pellet structure enhances mechanical integrity (Kaliyan and Morey, 2009).

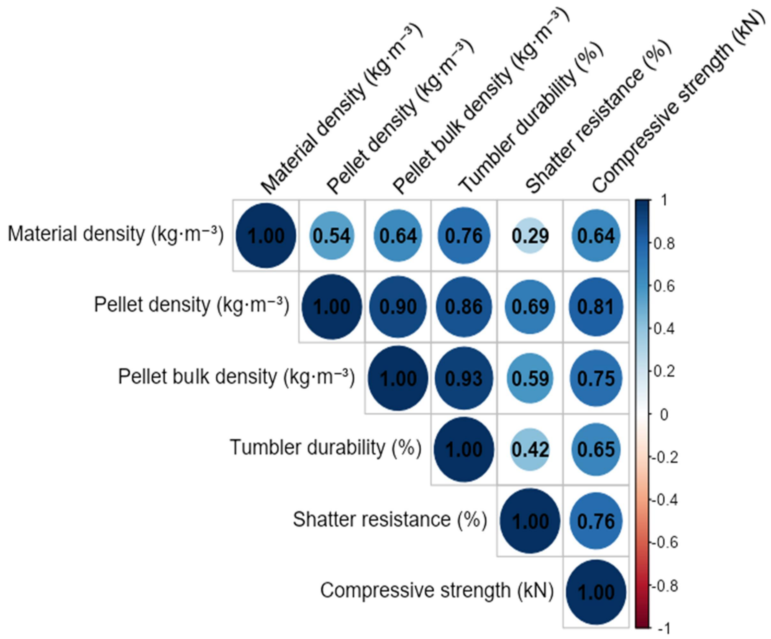

Figure 2. Pearson correlation matrix showing the relationships among physical and mechanical properties of pellets.

3.2. Principal component analysis (PCA) of physical and mechanical properties

Principal Component Analysis (PCA) was applied to comprehensively evaluate the relationships between the six physical and mechanical parameters measured. According to the PCA results, the first two principal components explain 89% of the total variance. The first principal component (PC1) explains 74% of the variance, while the second principal component (PC2) explains 14% (Table 3).

Table 3. Eigenvalues, explained variance ratios, and cumulative variance of principal components obtained from PCA based on physical and mechanical properties of pellets.

	PC1	PC2	PC3	PC4	PC5	PC6
Standard Deviation	2.11	0.92	0.67	0.39	0.27	0.13
Variance Ratio	0.74	0.14	0.07	0.02	0.01	0.00
Cumulative Variance	0.74	0.89	0.96	0.99	1.00	1.00

PC1 stands out as a component strongly related to the mechanical and structural quality characteristics of the pellets. In the PCA biplot graph (Figure 3), it can be seen that the vectors for pellet density, bulk density, tumbler resistance, impact resistance, and fracture resistance under pressure are largely aligned in the same direction and along the PC1 axis. This indicates that these parameters are highly positively correlated with each other and that PC1 primarily represents the dimension of “overall pellet quality and mechanical integrity.”

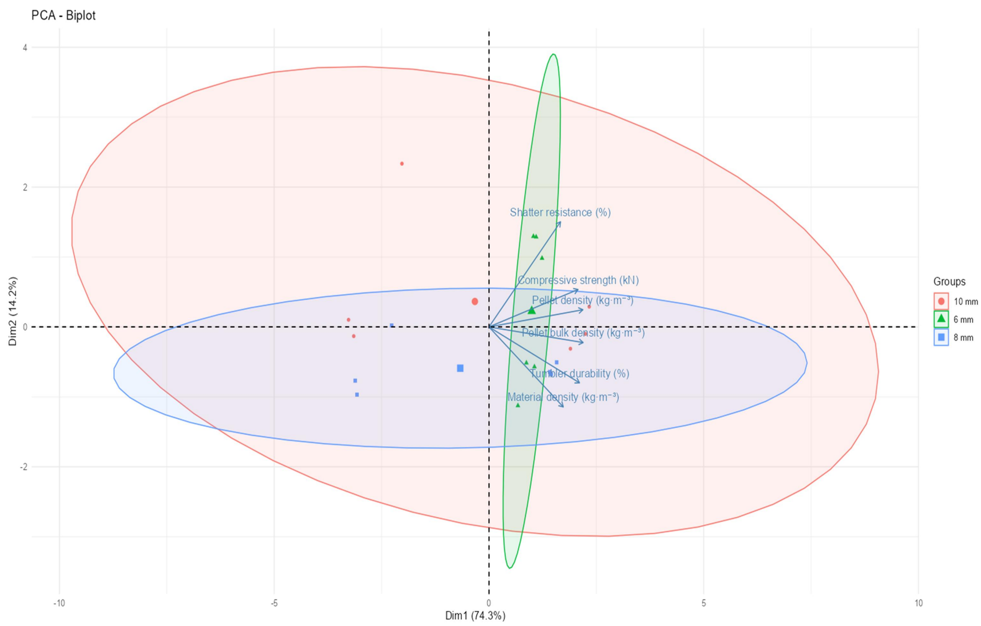

Figure 3. PCA biplot showing the relationships among physical and mechanical properties of pellets and the distribution of pellet diameter groups in the first two principal components.

In contrast, the contribution of the material density vector to PC1 is more limited, and it plays a weaker discriminating role compared to other quality parameters. This is consistent with the fact that material density exhibits lower variability compared to pellet product properties.

The second principal component (PC2) explains 14% of the variance, with shatter resistance and, to a lesser extent, compression resistance variables contributing more significantly to this axis (Figure 3). The limited distinction between groups along the PC2 axis indicates that this component represents secondary variations rather than the main factors determining pellet quality.

When examining the distribution of the experimental groups in the PCA biplot graph (Figure 3), it can be seen that the 6 mm diameter pellets are located in the direction of the mechanical strength, density, and pressure resistance vectors and therefore cluster in the high-quality region. In contrast, 10 mm diameter pellets are located further away from the mechanical strength and impact resistance vectors, representing groups with lower mechanical performance. 8 mm diameter pellets, on the other hand, show a distribution in an intermediate position between these two groups.

Overall, the PCA results revealed that mechanical strength, impact resistance, pressure resistance, and density parameters change together and are the fundamental factors determining pellet quality. PCA analysis confirmed the trends previously identified by individual statistical analyses and correlation results from a multivariate perspective and clearly showed that smaller pellets exhibit higher mechanical performance and integrity.

4. Discussion

The findings obtained in this study clearly demonstrate that moisture content and pellet diameter play a critical role in pellet production from tea waste. High moisture content (11–12%) improved pellet quality in almost every aspect; durability, impact resistance, and fracture strength were significantly higher compared to low moisture content. This is consistent with the fact that water acts as a natural adhesive during pelletization, facilitating the bonding of fibers (Ungureanu et al., 2018). The literature reports that moisture content in the range of 10–15% provides optimization for many biomasses, increasing both pellet density and mechanical strength (Serrano et al., 2011). In this study, it can be said that the optimal moisture range for tea waste is probably slightly above 10%. It has been observed that pellets become brittle at lower moisture levels, such as 8–9%, because lignin does not become sufficiently fluid and the interparticle bonds remain weak. The disadvantage of low moisture is particularly significant in large-diameter pellets, as these pellets accumulate more internal stress and crack easily under impact/vibration. On the other hand, increasing the moisture content beyond 11–12% will likely have the opposite effect, as excessive moisture can prevent sufficient friction in the pellet press, reduce density, and cause pellets to crack during drying (Ungureanu et al., 2018). Furthermore, pellets with high moisture content during storage become susceptible to fungal and microbial degradation (Cutz et al., 2021). Therefore, the most suitable moisture range for tea waste pelletization can be recommended as approximately 10–12%.

When examining the effects of pellet diameter, the experimental results generally indicate that smaller diameter pellets (6 mm) are more advantageous. The 6 mm pellets exhibited the highest mechanical strength and impact resistance, followed by the 8 mm pellets; the 10 mm pellets, however, performed poorly, especially under low humidity conditions. These findings are consistent with observations from some studies conducted with wood and agricultural waste pellets (Kuranc et al., 2020). Smaller pellets have a greater surface area per unit volume during compression, which may facilitate the homogeneous distribution of heat within the material and the escape of moisture. Furthermore, as the diameter decreases, the compression pressure per unit area may increase because the pelletizing machine applies the same pressure to a smaller area; this is a factor that increases the density and integrity of the pellet. Indeed, Tumuluru (2018) noted that an 8 mm die causes more moisture loss than a 10 mm die, and as a result, 8 mm pellets can be less dense in some cases. In our experiments, the density of 8 mm pellets was also found to be slightly lower than that of 10 mm pellets. However, in terms of durability, 8 mm pellets still performed better than 10 mm pellets. This can be interpreted as density alone not being the sole factor determining durability. Although 10 mm pellets have a higher density (especially in the high moisture group), the higher absolute moisture content trapped in their internal structure or microcracks formed during the cooling process may have negatively affected their durability. In the present study, although larger diameter pellets (10 mm) exhibited slightly higher bulk density, they showed lower durability due to the internal microcracks formed during cooling and moisture retention, which weakened the structural integrity of the pellets (Yaz, 2023; Yaz, 2024). In the study by Kuranc et al. (2020), 8 mm wood pellets also showed lower durability than 6 mm pellets, and the authors attributed this partly to the difference in geometric dimensions. However, conflicting results regarding diameter can be found in studies using different raw materials (Ungureanu, 2018; Rupasinghe et al., 2023; Svensson et al., 2024). In the example of Thanphrom et al. (2022), 10 mm green tea pellets were more durable than 7 mm pellets. This difference is a result of the pelletizing method used, the properties of the raw material (chemical structure of green tea waste, fiber length, etc.), and perhaps the different pellet lengths. Our experiments were conducted using a continuous-feed pellet machine, representing a process closer to practical application. In this regard, we can say that diameters in the 6–8 mm range are more suitable for producing tea waste pellet fuel. Looking specifically at standards for domestic heating purposes, a diameter of 6 or 8 mm is preferred; our findings show that this preference can also be technically supported.

All parameters evaluated in terms of pellet quality have changed in a holistic manner. Mechanical strength, impact resistance, and pressure resistance are positively correlated with each other and have responded together to improved test conditions (higher moisture, smaller diameter). This is important from a practical standpoint because, in general, a pellet's performance in different strength tests is consistent. For example, pellets with high durability are more resistant to manual breakage and generate less dust during handling, transportation, or silo unloading. Previous studies have demonstrated that pellets exhibiting high mechanical durability show significantly lower breakage and fines formation under handling and transport conditions (Temmerman et al., 2006; Demirel et al., 2020; Yıldız & Topkoç, 2023).Under our best conditions (11–12% moisture, 6 mm diameter), mechanical durability was 95%, impact resistance was 97%, and breaking load was ~0.5kN. These values were obtained using only tea waste without any additives and are considered satisfactory according to many standards. In contrast, under our most unfavorable conditions (8–9% moisture, 10 mm diameter), strength decreased to 65–70%, impact resistance to 75%, and breaking strength remained quite low at ~0.3 kN. Therefore, it is clear that conditions must be well-adjusted to produce high-quality pellets from tea waste.

Our results are consistent with the general trends in the literature, but they warrant discussion on certain specific points. For example, the higher bulk density of pellets with a 10 mm diameter may seem surprising at first glance, as it is commonly expected that smaller pellets would be denser. However, Tumuluru (2018) noted that when a 10 mm die is used in the pelletization of high-moisture biomass, some of the moisture is retained within the pellet, and during cooling and hardening, the pellets achieve a dense structure. In our experiments, 10 mm pellets also cooled relatively slowly, especially under high moisture conditions, and likely shrank by trapping some moisture inside. As a result, although their density was slightly higher than that of 8 mm pellets, they did not offer any advantage in terms of strength due to internal stresses.

Furthermore, the low bulk density of 10 mm pellets is a disadvantage for storage and feeding; they contain less mass for the same volume and are more likely to bridge in automatic feeding systems. Therefore, if tea waste pellets are to be marketed, a diameter of 6 or 8 mm would be more suitable in terms of both quality and logistics.

The correlation analysis results revealed that the physical and mechanical quality parameters of the pellets change together to a large extent. In particular, the positive relationships observed between mechanical durability (tumbler durability) and fracture resistance under pressure and impact resistance indicate that different durability tests consistently reflect pellet integrity. Similarly, the strong positive correlations between pellet density and bulk density and mechanical durability indicate that denser and more compactable pellets generally exhibit higher mechanical performance. This can be explained by the reduction in void ratio within the pellet structure limiting crack formation and making load transfer more homogeneous. Indeed, the literature frequently reports that increased density positively affects pellet durability (Kaliyan and Morey, 2009). However, it should be noted that correlation analysis does not indicate causality and only reveals the co-variation between variables. In this context, the correlation results support the individual experimental findings that reveal the effects of moisture content and pellet diameter on quality, indicating that pellet quality exhibits a multi-parameter structure.

PCA results have been useful in comprehensively visualizing the combined effect of different experimental conditions on pellet properties. In the PCA biplot, experimental groups representing high moisture and small diameter conditions and groups representing low moisture and large diameter conditions were positioned in opposite regions on the first two principal component planes. This situation indicates that the experimental conditions examined clearly distinguish the physical and mechanical properties of the pellets. The first principal component (PC1) explains a large portion of the total variance and represents parameters directly related to quality, such as mechanical strength, impact resistance, fracture resistance under pressure, and pellet and bulk density, with high positive loadings. Therefore, PC1 can be defined as the “general pellet quality and mechanical integrity axis”. As we move along the PC1 axis, we see that the pellets' strength and density values increase, while the test groups representing lower quality are located on the negative side of this axis. This finding is consistent with the widely accepted general principle that “better compacted and stronger pellets exhibit higher quality.” The second principal component (PC2) explains a more limited portion of the total variance, reflecting secondary variations associated with parameters such as impact resistance and, to a lesser extent, compressive strength. The relatively weak distinction between groups along PC2 indicates that this component represents secondary effects rather than the primary factors determining pellet quality. This is a natural consequence of keeping variables such as feedstock type and particle size constant within the experiment. Overall, the PCA analysis revealed that pellet durability, impact resistance, compressive strength, and density parameters change together and that pellet quality exhibits a multidimensional yet consistent structure. These results are consistent with individual statistical analyses and correlation findings, indicating that compression conditions and moisture control should be among the key priorities in future studies involving different biomass types or pre-treatment conditions.

5. Conclusions

In this study, the pelletability of tea waste under different moisture contents and pellet diameters, as well as the physical and mechanical properties of the pellets obtained, were comprehensively evaluated. The results revealed that moisture content directly and strongly affects pellet quality; It was determined that a medium moisture content of 11–12% significantly increases pellet density, mechanical strength, impact resistance, and fracture resistance under pressure, whereas low moisture levels of 8–9% cause pellets to be more brittle and less durable. In this context, it can be said that moisture levels in the range of approximately 10–12% offer an appropriate balance for tea waste under the conditions examined. When evaluating the effects of pellet diameter, it was found that as the diameter decreased, the mechanical strength, impact resistance, and fracture resistance values of the pellets increased; 6 mm diameter pellets exhibited the best quality characteristics, while 10 mm diameter pellets showed the weakest performance, especially under low moisture conditions. Therefore, it is understood that pelletizing tea waste at smaller diameters such as 6–8 mm is more advantageous in terms of product quality. When examining the density values, it was determined that the raw material density increased significantly with the pelletization process; the piece density of the pellets obtained was approximately 1150–1250 $kg.m^{-3}$, and the bulk density was in the range of 550–650 $kg.m^{-3}$. It was observed that the bulk density decreased as the pellet diameter increased, with the value of approximately 630 $kg.m^{-3}$ for 6 mm pellets dropping to approximately 560 $kg.m^{-3}$ for 10 mm pellets; however, it was determined that the bulk density of all groups generally met the lower limits specified in the biofuel pellet standards. Mechanical strength (Tumbler test) results varied between 65–95%; the highest durability value (95%) was measured in high-moisture 6 mm pellets, while the lowest durability (65–70%) was determined in low-moisture 10 mm pellets, confirming that both moisture content and pellet diameter have statistically significant effects on durability. Similarly, Shatter (impact) test results yielded retention rates between 75–97%; high-moisture and small-diameter pellets were found to be extremely resistant to impact, while low-moisture and large-diameter pellets suffered breakage at a rate of approximately one-quarter. Fracture resistance under pressure was measured at approximately 0.5 kN under the best conditions and 0.3 kN under the most unfavorable conditions; it was determined that increased moisture significantly increased fracture resistance, while the effect of pellet diameter was more limited compared to mechanical durability. Statistical analyses revealed that moisture content and pellet diameter have significant effects on all quality parameters. Correlation analysis identified positive relationships between pellet density, mechanical durability, and fracture resistance, while negative relationships were found between pellet diameter and these properties. PCA results also clearly showed that the combination of high moisture and small diameter is associated with high-quality pellets. In conclusion, it can be said that tea waste can be converted into a quality pellet fuel without the need for any binder under appropriate conditions, which means that an important biomass potential can be converted into energy for tea-producing countries such as Türkiye. In terms of application, when pelletizing tea waste, not over-drying the raw material, pelletizing at approximately 10–12% moisture content, and preferring pellet production with a diameter of 6–8 mm provides advantages in terms of the product's mechanical strength and compliance with market standards. The fact that the pellets obtained exhibit properties close to conventional wood pellets in terms of density and durability strengthens the potential of tea waste as an alternative biofuel raw material. Approaches such as adding natural binders at low rates or mixing tea waste with woody waste for future applications requiring higher durability are also considered worth investigating.

Conflicts of Interests

Authors declare that there is no conflict of interests

Financial Disclosure

Author declare no financial support.

References

1. Bajwa, D. S., Peterson, T., Sharma, N., Shojaeiarani, J., & Bajwa, S. G. (2018). A review of densified solid biomass for energy production. Renewable and Sustainable Energy Reviews, 96, 296-305. https://doi.org/10.1016/j.rser.2018.07.040
2. Bilgin, S., Koçer, A., Yılmaz, H., Acar, M., & Dok, M. (2016). Çay fabrikası atıklarınının peletlenmesi ve pelet fiziksel özelliklerinin belirlenmesi. Journal of Agricultural Faculty of Gaziosmanpaşa University (JAFAG), 33 (Ek sayı), 70-80.
3. Cutz, L., Tiringer, U., Gilvari, H., Schott, D., Mol, A., & de Jong, W. (2021). Microstructural degradation during the storage of biomass pellets. Communications Materials, 2 (1), 2. https://doi.org/10.1038/s43246-020-00113-y
4. Demirel, B. (2023). Determination of solid biofuel properties of hazelnut husk briquettes obtained at different compaction pressures. Biomass Conversion and Biorefinery, 13 (14), 13267-13278. https://doi.org/10.1007/s13399-023-04431-2
5. Demirel, B., & Gürdil, G. (2022). Physical-Mechanical Parameters of Hazelnut Husk Bio-Briquettes Produced by a Horizontal Pressing Briquetting Machine. Black Sea Journal of Agriculture, 5 (4), 476-480. https://doi.org/10.47115/bsagriculture.1169764
6. Demirel, C., Gürdil, G. A. K., Kabutey, A., & Herak, D. (2020). Effects of forces, particle sizes, and moisture contents on mechanical behaviour of densified briquettes from ground sunflower stalks and hazelnut husks. Energies, 13 (10), 2542. https://doi.org/10.3390/en13102542
7. Dok M (2014). Karadeniz Bölgesinin tarımsal atıkpotansiyeli ve bunlardan pelet yakıt olarak yararlanılması. 4th National Workshop on Energy Agriculture and Biofuels, May 28–29, 2014, s. 211-222, Samsun.
8. EN 14961-2:2011, Solid biofuels — Fuel specifications and classes — Part 2: Wood pellets.

9. Filbakk, T., Skjevrak, G., Høibø, O., Dibdiakova, J., & Jirjis, R. (2011). The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters. Fuel Processing Technology, 92 (5), 871-878. https://doi.org/10.1016/j.fuproc.2010.12.001
10. Gürdil, G. (2020). Environmental impact of bio-briquettes produced from agricultural residues concerning to CO2 emissions. Mustafa Kemal Üniversitesi Tarım Bilimleri Dergisi, 25 (2), 217-224. https://doi.org/10.37908/mkutbd.735750
11. He, H., Wang, Y., Sun, Y., Sun, W., & Wu, K. (2024). From raw material powder to solid fuel pellet: A state-of-the-art review of biomass densification. Biomass and Bioenergy, 186, 107271. https://doi.org/10.1016/j.biombioe.2024.107271
12. Kaliyan, N., & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. Biomass and bioenergy, 33 (3), 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005
13. Kuranc, A., Stoma, M., Rydzak, L., & Pilipiuk, M. (2020). Durability Assessment of wooden pellets in relation with vibrations occurring in a logistic process of the final product. Energies, 13 (22), 5890. https://doi.org/10.3390/en13225890
14. Li, W., Wang, M., Meng, F., Zhang, Y., & Zhang, B. (2022). A review on the effects of pretreatment and process parameters on properties of pellets. Energies, 15 (19), 7303. https://doi.org/10.3390/en15197303
15. Lunguleasa, A., Olarescu, A., & Spirchez, C. (2024). Pellets obtained from the husks of sunflower seeds and beech sawdust for comparison. Forests, 15(6), 902. https://doi.org/10.3390/f15060902
16. Mignogna, D., Szabó, M., Ceci, P., & Avino, P. (2024). Biomass Energy and Biofuels: Perspective, Potentials, and Challenges in the Energy Transition. Sustainability, 16 (16), 7036. https://doi.org/10.3390/su16167036
17. Miranda, T., Montero, I., Sepúlveda, F. J., Arranz, J. I., Rojas, C. V., & Nogales, S. (2015). A review of pellets from different sources. Materials, 8 (4), 1413-1427. https://doi.org/10.3390/ma8041413
18. Mortadha, H., Kerrouchi, H. B., Al-Othman, A., & Tawalbeh, M. (2025). A comprehensive review of biomass pellets and their role in sustainable energy: production, properties, environment, economics, and logistics. Waste and Biomass Valorization, 16 (9), 4507-4539. https://doi.org/10.1007/s12649-024-02873-x
19. Mostafa, M. E., Hu, S., Wang, Y., Su, S., Hu, X., Elsayed, S. A., & Xiang, J. (2019). The significance of pelletization operating conditions: An analysis of physical and mechanical characteristics as well as energy consumption of biomass pellets. Renewable and Sustainable Energy Reviews, 105, 332-348. https://doi.org/10.1016/j.rser.2019.01.053
20. Picchio, R., Latterini, F., Venanzi, R., Stefanoni, W., Suardi, A., Tocci, D., & Pari, L. (2020). Pellet production from woody and non-woody feedstocks: A review on biomass quality evaluation. Energies, 13 (11), 2937. https://doi.org/10.3390/en13112937
21. Ribeiro, G. F., & Junior, A. B. (2023). The global energy matrix and use of agricultural residues for bioenergy production: A review with inspiring insights that aim to contribute to deliver solutions for society and industrial sectors through suggestions for future research. Waste Management & Research, 41 (8), 1283-1304. https://doi.org/10.1177/0734242X231154149
22. Rupasinghe, R. L., Perera, P., Bandara, R., Amarasekera, H., & Vlosky, R. (2023). Insights into properties of biomass energy pellets made from mixtures of woody and non-woody biomass: a meta-analysis. Energies, 17 (1), 54. https://doi.org/10.3390/en17010054
23. Sarker, T. R., Nanda, S., Meda, V., & Dalai, A. K. (2023). Densification of waste biomass for manufacturing solid biofuel pellets: a review. Environmental Chemistry Letters, 21 (1), 231-264. https://doi.org/10.1007/s10311-022-01510-0
24. Serrano, C., Monedero, E., Lapuerta, M., & Portero, H. (2011). Effect of moisture content, particle size and pine addition on quality parameters of barley straw pellets. Fuel Processing Technology, 92 (3), 699-706. https://doi.org/10.1016/j.fuproc.2010.11.031
25. Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012). Recent developments in biomass pelletization-a review. BioResources, 7 (3), 4451-4490. https://doi.org/10.15376/biores.7.3.stelte
26. Svensson, A., Almarstrand, M., Axelsson, J., Nilsson, M., Timmermann, E., & Govindarajan, V. (2024). Valorising Agricultural Residues into Pellets in a Sustainable Circular Bioeconomy. Problemy Ekorozwoju, 19 (2). https://doi.org/10.35784/preko.5808
27. Temmerman, M., Rabier, F., Jensen, P. D., Hartmann, H., & Böhm, T. (2006). Comparative study of durability test methods for pellets and briquettes. Biomass and Bioenergy, 30 (11), 964-972. https://doi.org/10.1016/j.biombioe.2006.06.008

28. Thanphrom, S., Hunt, A. J., Macquarrie, D. J., & Ngernyen, Y. (2022). Valorization of green tea waste from ready-to-drink industry through pelletization and use as solid fuel. Asia-Pacific Journal of Science and Technology. https://doi.org/10.14456/apst.2022.18
29. Tumuluru, J. S. (2018). Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. Carbon Resources Conversion, 1 (1), 44-54. https://doi.org/10.1016/j.crcon.2018.06.002
30. Ungureanu, N., Vladut, V., Voicu, G., Dinca, M. N., & Zabava, B. S. (2018). Influence of biomass moisture content on pellet properties–review. Engineering for Rural Development, 17, 1876-1883. https://doi.org/10.22616/ERDev2018.17.N449
31. Yaz, M. (2023). Adhesive wear behavior of FeB–FeMn–C coatings produced by GTAW. Materials Testing, 65 (8), 1190-1201. https://doi.org/10.1515/mt-2023-0164
32. Yaz, M. (2024). Adhesive wear behavior and microstructure of FeCr–FeMn–FeB–C coatings. Materials Testing, 66 (1), 75-87. https://doi.org/10.1515/mt-2023-0347
33. Yıldız, Z., & Topkoç, E. (2023). Tarımsal atıklardan elde edilen biyopeletlerin bazı yakıt özelliklerinin uluslararası pelet standartları ile karşılaştırılması. Artvin Çoruh Üniversitesi Orman Fakültesi Dergisi, 24 (2), 1-9. https://doi.org/10.17474/artvinofd.1231448
34. Yılmaz, H. (2018). Mısır saplarının peletlenmesi ve pelet özelliklerinin belirlenmesi. Mediterranean Agricultural Sciences, 31 (3), 269-274. https://doi.org/10.29136/mediterranean.427730

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual authors and contributors and not of IJNLS and/or the editors. IJNLS and/or the editors disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.