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# Comparative Study of the Effect of Thermal Treatment on the Hardness of Jumbo, Medium and Small Cashew Nut Shells

**Jimeshio, Joseph Gberindyer[1], Ekemube, Raymond Alex[2], Nyamkyume, Felix Terkula[3], Yahaya, Timothy Ojoarome[4]**

[1]Value Addition Research, Cocoa Research Institute of Nigeria (CRIN), Ibadan, Oyo State, jimeshiojoseph1@gmail.com
[2]Department of Agricultural and Biosystems Engineering, University of Benin, Benin City, raymond.ekemube@uniben.edu
[3]Department of Plant Breeding, Cocoa Research Institute of Nigeria (CRIN), Ibadan, Oyo State, nyamkyumeterkula@gmail.com
[4]Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, Kaduna State, tuwasta4real@yahoo.com

***Abstract****: Cashew nut shells (CNS) are sufficient agro-industrial residues with potential for biomass utilization, particularly briquette production. However, hardness influences their biomass conversion performance. This study compared the effects of thermal treatment temperature and duration on jumbo, medium, and small CNS hardness and evaluated their individual and combined effects using two-way ANOVA. The classification of cashew nut was done on the basis of their individual weights, Jumbo weighs (≥16 g), medium (≥ 8 g), and small (≥ 6 g), the cashew nut shells were treated for 30, 60, and 90 minutes at 200, 250, and 300°C. Universal Testing Machine was used to determine hardness; a two-way ANOVA was used to evaluate the results at 5% significance level. Hardness for jumbo shells was significantly affected by temperature (F = 8.59, p = 0.0024) and duration (F = 10.01, p = 0.0012), but their interaction was not significant (F = 0.997, p = 0.4344). For medium shells, treatment duration was significant (F = 5.17, p = 0.0169), whereas treatment temperature (F = 2.11, p = 0.1507) and interaction (F = 0.189, p = 0.9412) were not significant. For small shells, treatment temperature was significant (F = 4.09, p = 0.0344), while treatment duration (F = 0.453, p = 0.6428) and interaction (F = 1.434, p = 0.2634) were not significant. Medium shells exhibited higher hardness than jumbo and small shells. The findings demonstrated size-dependent thermal responses and highlighted the importance of considering shell size when selecting thermal treatment conditions for CNS biomass utilization.*

**Keywords:** *Cashew nut shell, hardness; thermal treatment, heating duration, temperature, Universal Testing Machine, two-way ANOVA*

## 1. Introduction

Global production of cashew nuts (Anacardium occidentale *L*.) has continued to increase over the past decade, making cashew one of the fastest-growing tree nut commodities worldwide (UNCTAD, 2021). Africa has emerged as the major production region, while Asia remains the dominant processing hub. Nigeria is among Africa's leading cashew-producing countries, supported by favourable agro-ecological conditions, expanding domestic processing industries, and government initiatives aimed at promoting agricultural exports (UNCTAD, 2021; FAOSTAT, 2024). The shell constitutes approximately 50–60% of the total raw cashew nut mass**,** the continued expansion of global cashew processing has resulted in the generation of substantial quantities of cashew nut shells (CNS), traditionally regarded as low-value agro-industrial residues, these shells are now increasingly recognized as valuable lignocellulosic biomass because of their high content of cashew nut shell liquid (CNSL), cellulose, hemicellulose, and lignin, making them suitable feedstocks for bioenergy, biochemicals, and advanced biomaterials (Mubofu and Mgaya, 2018; Mgaya *et al*., 2019; Nyirenda *et al*., 2021).

The rapid expansion of cashew processing across Africa and other major producing regions between 2022 and 2025, substantial quantities of cashew nut shells (CNS) are generated annually, creating both environmental challenges and opportunities for value addition. In many processing facilities, these shells are still disposed of through open burning or inefficient combustion, contributing to greenhouse gas emissions, localized air pollution, and the loss of valuable lignocellulosic biomass resources (Alaka *et al*., 2024; Jana *et al*., 2024). Furthermore, the phenolic-rich cashew nut shell liquid (CNSL), which contains bioactive compounds such as anacardic acids, cardanol, and cardol, poses environmental risks if improperly handled or released into the environment, although these compounds also offer significant potential as renewable feedstocks for the production of bio-based chemicals, polymers, coatings, and advanced materials (Alaka *et al*., 2024; Nayak *et al*., 2024; Bhatia *et al*., 2024). Consequently, sustainable utilization and valorization of CNS have become central to circular bio-economy strategies aimed at reducing agro-industrial waste while improving resource efficiency and environmental sustainability.

Agricultural residues such as cashew nut shells (CNS) have attracted increasing research interest owing to the global drive toward biomass valorization, renewable energy systems, and the circular bio-economy (International Energy Agency (IEA), 2023; United Nations Conference on Trade and Development (UNCTAD), 2021). Rich in lignocellulosic components and possessing a relatively high calorific value, CNS has emerged as a promising renewable feedstock for the production of solid biofuels, activated carbon, bio-oil through pyrolysis, and other thermochemical conversion products (Mgaya *et al*., 2019; Nyirenda *et al*., 2021; Jana *et al*.,

2024). Nevertheless, the successful utilization of cashew nut shells in these applications depends largely on their engineering and mechanical properties, particularly hardness, which influences grinding energy, handling, densification behaviour during briquetting, storage stability, and the efficiency of thermochemical conversion processes (Mgaya *et al*., 2019; Jana *et al*., 2024).

Hardness is a fundamental mechanical property that describes the resistance of cashew nut shells (CNS) to localized deformation, indentation, and fracture under applied mechanical loads (Jimeshio, *et al*., 2026). This property plays a critical role in shell crushing, milling, densification, briquetting, and other mechanical processing operations because it influences energy consumption, equipment wear, and the quality of value-added products (Cruz *et al*., 2024; Ningthoujam *et al*., 2024). The mechanical behaviour of CNS is governed by its unique anatomical and physicochemical structure, consisting of a rigid shell impregnated with cashew nut shell liquid (CNSL) and a lignocellulosic matrix that contributes to its high mechanical strength and thermal stability (Cruz *et al*., 2024; Rojtman *et al*., 2024). Chemically, cashew nut shells are composed primarily of cellulose, hemicellulose, lignin, and phenolic compounds, particularly anacardic acids, cardanol, and cardol, whose interactions determine the shell's hardness, stiffness, and resistance to degradation (Jana *et al*., 2024; Rojtman *et al*., 2024). The cellulose-rich fibrous framework provides structural reinforcement, while lignin and phenolic constituents act as natural binding agents that enhance rigidity and durability, making CNS an attractive feedstock for briquetting, pyrolysis, activated carbon production, and other thermochemical conversion technologies (Jana *et al*., 2024; Cruz *et al*., 2024).

Driven by the global transition towards renewable energy systems, biomass valorization, and circular bio-economy strategies, agricultural residues such as cashew nut shells (CNS) are increasingly recognized as sustainable feedstocks for industrial and energy applications (UNCTAD, 2021;IEA, 2023). Owing to their high carbon content, favourable calorific value, and lignocellulosic composition, cashew nut shells have attracted considerable attention for the production of solid biofuels, activated carbon, biochar, pyrolysis oil, gasification feedstocks, and other value-added products (Nyirenda *et al*., 2021; Kadjo *et al*., 2024; Alaka *et al*., 2024). However, the performance and efficiency of these applications depend not only on the chemical composition of the shells but also on their engineering and mechanical properties, particularly hardness, which governs their resistance to mechanical deformation during crushing, handling, densification, transportation, and thermochemical processing.

Controlled thermal treatment has been shown to significantly modify the physicochemical, thermal, and energetic properties of cashew nut shells (CNS), thereby enhancing their suitability for bioenergy and other value-added applications (Jimeshio *et al*., 2026). Heat treatment influences important characteristics including moisture content, volatile matter, residual cashew nut shell liquid (CNSL), energy density, heating value, and thermal degradation behaviour, with the extent of these changes depending on the treatment temperature and residence time (Cruz *et al*., 2024; Kadjo*et al*., 2024). During thermal treatment, biomass undergoes progressive moisture evaporation, volatilization of extractives, degradation of hemicellulose and cellulose, partial restructuring of the lignin matrix, and changes in the physicochemical composition of the shell. These transformations alter the mechanical integrity, dimensional stability, density, and hardness of the lignocellulosic structure, thereby affecting its performance during densification, briquetting, storage, and thermochemical conversion processes (Kadjo *et al*., 2024).

Under controlled thermal treatment, cashew nut shells (CNS) undergo progressive physicochemical transformations that significantly influence their engineering properties. During the initial heating stage (approximately 100–150 °C), free and bound moisture are removed, thereby improving dimensional stability and reducing hygroscopicity. As the treatment temperature increases to approximately 200–260 °C, hemicellulose begins to decompose, while constituents of cashew nut shell liquid (CNSL), particularly anacardic acids, undergo decarboxylation to form cardanol, accompanied by the volatilization and partial polymerization of phenolic compounds (Cheng *et al*., 2023; Rojtman *et al*., 2024). At higher temperatures (above 280–300 °C), progressive cellulose degradation and lignin restructuring promote carbonization, increased porosity, mass loss, and significant changes in the mechanical behaviour of the shell (Kadjo *et al*., 2024; Silva *et al*., 2024). These thermochemical transformations modify the lignocellulosic matrix and consequently influence the hardness, dimensional stability, and structural integrity of the biomass, thereby determining its suitability for briquetting, thermochemical conversion, and other bioenergy applications (Cruz *et al*., 2024; Kadjo *et al*., 2024).

Cashew germplasm maintained by the Cocoa Research Institute of Nigeria (CRIN), Ibadan, comprises distinct nut size categories, including jumbo, medium, and small biotypes, which differ in nut weight, shell dimensions, and other morphological characteristics important for breeding and industrial processing (CRIN, 2023; Adeniyi *et al*., 2021). These morphological variations are expected to influence heat transfer during thermal treatment because shell thickness, geometry, and structural characteristics govern the rate of heat penetration and internal temperature distribution. Larger shells generally possess thicker shell walls and greater structural rigidity, whereas smaller shells are likely to heat more rapidly owing to their reduced thickness and lower thermal resistance (Maranon *et al*., 2024). Furthermore, differences in shell morphology and internal structure contribute to variations in mechanical properties, including compressive behaviour and resistance to deformation, suggesting that shell size may significantly influence hardness responses during thermal treatment (Cruz *et al*., 2024; Maranon *et al*., 2024).

Despite the increasing utilization of cashew nut shells (CNS) for renewable energy, bio-based materials, and circular bio-economy applications, previous research has focused predominantly on their chemical composition, cashew nut shell liquid (CNSL), pyrolysis characteristics, biochar production, thermochemical conversion, and energy recovery (Nyirenda *et al*., 2021; Cruz *et al*., 2024; Kadjo *et al*., 2024). Comparatively little attention has been devoted to understanding how controlled thermal treatment influences the engineering and mechanical properties of CNS, particularly hardness, which is an important parameter in crushing, densification, briquetting, and material handling. Furthermore, most published studies treat cashew nut shells as a homogeneous biomass resource without considering variations associated with shell size or morphology, despite evidence that physical characteristics such as shell dimensions, wall thickness, and internal structure influence heat transfer, thermal degradation, and mechanical behaviour (Cruz *et al*., 2024;Maranon *et al*., 2024).

Consequently, the individual and interactive effects of treatment temperature and heating duration on the hardness of different cashew nut shell size categories remain inadequately understood. Addressing this knowledge gap is essential for comparing thermal pretreatment conditions on the hardness of the different morphology of cashew nut shells and improving the engineering utilization of cashew nut shells in briquette production, biochar manufacture, composite materials, and other biomass conversion technologies.

## 2. Materials and Methods

The materials used during the research include; Cashew nut shells, universal testing machine, stop watch, weighing balance, vernier caliper sample nylons and gloves, distilled water, and thermometer.

### 2.1 Description of Study Area

Samples of cashew nuts were collected from the cashew germplasm of Cocoa Research Institute of Nigeria (CRIN), Ibadan which is situated in the Oluyole Local Government Area of Ibadan, Oyo State, Nigeria (Latitude 07°10' N Longitude 03°52' E) with a bimodal rainfall pattern (Oyo State Government, 2021;CRIN, 2022).

### 2.2 Sample Preparation

The samples were divided into three size categories based on predetermined mass ranges measured with a digital analytical balance with an accuracy of (±0.01 g), as shown in Plate 1, cashew nut shells were cleaned to remove adhering foreign materials. The characterization was carried out in the department of agronomy of the Cocoa Research Institute of Nigeria (CRIN), Ibadan. The jumbo cashew nut weighed (≥ 16g), the medium cashew nut weighed (6–8g), and the small weighed (2–6g). A total of 3,000 shell samples were used, 1,000 of each were labeled and kept in ambient laboratory settings before additional examination.



**Plate 1**: Digital analytical balance

Samples were cut into two distinct parts using a manually operated cashew nut cracker in the department of Value Addition Research of Cocoa Research Institute of Nigeria, Ibadan for mechanical testing as shown in Plate 2. All samples were oven-dried at 105°C for 4 hours to remove moisture and standardize initial conditions as presented in plate 3.(Jimeshio, *et al*., 2025).





**Plate 2**: Manually Operated cashew nut cracker **Plate 3:** Oven-drying at 105°C for 4 hours

### 2.3 Thermal Treatment

Cashew nut shells were subjected to thermal treatment at temperatures of 200°C, 250°C, and 300°C for durations of 30, 60, and 90 minutes in an oven as shown in Plate 4. After treatment, samples were allowed to cool to ambient laboratory conditions to prevent moisture reabsorption before testing as shown in Plate 5. The thermal treatment of cashew nut shells was conducted in the department of agricultural engineering of National Center for Agricultural Machinery (NCAM), Ilorin.





**Plate 4:** Thermal treatment of Cashew nut shells **Plate 5:** Cooling of cashew nut shells

### 2.4 Experimental Design

Hardness was the dependent variable in the study, which used a completely randomized design (CRD) set up in a $3^3$ factorial experiment. The independent variables were treatment temperature (200, 250, and 300°C), treatment duration (30, 60, and 90 min), and shell size (jumbo, medium, and small). Every combination of treatments was repeated three times. The datasets were analyzed using a three-way ANOVA.

### 2.5 Determination of Hardness

Hardness was determined using a Universal Testing Machine (UTM), model CPS 150 kN (15-ton capacity), manufactured by Fine Tech Indian OEM in an ISO 9001-certified facility. The machine operates with a load measurement accuracy of ±1% and displacement accuracy of ±0.5%, conforming to ISO 7500-1 Class 1 specifications as shown in the Plate 6.



**Plate 6:** Determination of hardness of cashew nut shell

When samples were compressed axially, the force at the breaking point was used to calculate the hardness. Samples were positioned in the middle of the UTM's compression platens and subjected to progressively higher compressive loads until they broke or underwent irreversible deformation. The computerized control panel directly recorded the maximum force prior to failure. Every test was carried out in compliance with the applicable ISO and ASTM standards for mechanical property assessment similar to Jimeshio, *et al*., (2025)

### 2.6 Statistical Analysis

Data obtained were subjected to two-way analysis of variance (ANOVA) using Microsoft Excel statistical software to determine the effects of the treatment factors and their interactions. Differences among treatment means were considered significant at the 5% probability level ($p < 0.05$). All measurements were conducted in triplicate, and results are presented as mean ± standard deviation (SD) similar to Steel *et al*., (1997) and Montgomery, (2020).

## 3. Results and Discussion

### 3.1 Effect of Treatment Temperature and Time on hardness of jumbo, medium and small cashew nut shells

The hardness of cashew nut shells was significantly affected by treatment temperature and duration ($p < 0.05$). Table 1 presents the mean hardness values for the jumbo, medium, and small cashew nut shell size categories across all temperature–time treatment combinations.

**Table 3.1: Comprehensive average Hardness results for Jumbo, Medium and Small Cashew Nut Shells at All Treatment Conditions**

| Variety | Temperature(°C) | Time (min) | Hardness |
|---|---|---|---|
| Jumbo | 200 | 30 | 57 |
| | | 60 | 41 |
| | | 90 | 33 |
| | 250 | 30 | 55 |
| | | 60 | 40 |
| | | 90 | 37 |
| | 300 | 30 | 34 |
| | | 60 | 31 |
| | | 90 | 27 |
| Medium | 200 | 30 | 97 |
| | | 60 | 81 |
| | | 90 | 65 |
| | | 30 | 95 |
| | 250 | 60 | 76 |
| | | 90 | 37 |
| | 300 | 30 | 78 |
| | | 60 | 51 |

| | | | |
|---|---|---|---|
| | | 90 | 21 |
| Medium | 200 | 30 | 16 |
| | | 60 | 40 |
| | | 90 | 31 |
| | 250 | 30 | 41 |
| | | 60 | 55 |
| | | 90 | 63 |
| | 300 | 30 | 65 |
| | | 60 | 34 |
| | | 90 | 38 |

**3.2** The two-way analysis of variance (ANOVA) as presented in tables 3.2 revealed that both treatment duration and thermal treatment temperature significantly influenced the hardness of jumbo cashew nut shells ($p < 0.05$), However, there was no statistically significant interaction between the two covariates ($p > 0.05$). Hardness was significantly impacted by treatment duration ($F = 10.01$, $p = 0.0012$), suggesting that variations in heating time led to quantifiable changes in the shells' mechanical resistance. Hardness was also significantly affected by treatment temperature ($F = 8.59$, $p = 0.0024$), indicating that thermal intensity also had a role in the observed variation. However, the non-significant interaction effect ($F = 0.997$, $p = 0.434$) suggests that temperature had no bearing on the impact of treatment duration on hardness, and vice versa. The mean hardness values further demonstrated that the shells became progressively less hard with increasing treatment duration, decreasing from 16.22N at 30 min to 12.33N at 60 min and 10.78N at 90 min. Similarly, hardness values were found at 200°C (14.56N) and 250°C (14.67N), however at 300°C (10.11N), there was a noticeable decrease. This pattern implies that whereas exposure to 300°C caused significant thermal deterioration of the lignocellulosic matrix similar to Liu *et al*., (2025), mild heating mostly eliminate free and bound moisture, leading to minor structural consolidation similar to Hubbe, *et al*., (2018). At this temperature, cellulose starts to depolymerize and hemicellulose degrades extensively similar to Wang *et al*., (2024) creating holes and microcracks that lessen the shell's resistance to indentation similar to Chu *et al*., (2025). From the result, the shell's hardness decreased when these structural polymers deteriorate similar to Mandala *et al*., (2023)

The significant influence of treatment duration observed in the present study agrees with the findings of Adeleke *et al*. (2022), who reported that prolonged thermal exposure progressively reduces the mechanical strength of lignocellulosic biomass due to degradation of hemicellulose and weakening of intermolecular bonding. Likewise, the significant effect of temperature corroborates the observations of Boua *et al*. (2024), who found that increasing thermal intensity modifies the mechanical behaviour of agricultural residues by altering their chemical composition and microstructure. The reduction in hardness at elevated temperatures is therefore consistent with the established thermal decomposition sequence of biomass constituents, where hemicellulose degrades first, followed by partial cellulose decomposition, while lignin softens over a broader temperature range which agrees with the findings of Yang *et al*., (2007).

Although some studies have reported a stronger interaction between treatment temperature and heating duration, the present study found no statistically significant interaction between these factors similar to Zhu *et al*.. (2026). This difference may be attributed to the relatively narrow temperature range investigated (200 - 300°C), the inherent thermal stability imparted by the high lignin and cashew nut shell liquid (CNSL) contents of cashew nut shells, and differences in shell geometry and heating conditions compared with other biomass materials. The absence of a significant interaction suggests that the effects of temperature and treatment duration were additive rather than synergistic similar to Adout *et al*., 2012 and (Nur) *et al*., 2012, implying that each factor independently influenced the hardness of the jumbo shells within the investigated processing conditions. The findings demonstrated that both treatment duration and temperature are important determinants of the hardness of jumbo cashew nut shells, with prolonged heating and excessive thermal intensity resulting in progressive deterioration of the shell's mechanical integrity which agrees with the findings of Jiang *et al*., (2022). These results provided valuable information for selecting thermal pretreatment conditions that preserve the structural properties of jumbo cashew nut shells intended for engineering and biomass utilization applications.

**Table 3.2**: Two-Factor ANOVA With Replication for Hardness of Jumbo cashew nut shells

| SUMMARY | 200 | 250 | 300 | Total |
|---|---|---|---|---|
| *30* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 57 | 55 | 34 | 146 |
| Average | 19 | 18.33333 | 11.33333 | 16.22222 |

| | | | | |
|---|---|---|---|---|
| Variance | 13 | 10.33333 | 10.33333 | 21.94444 |

| *60* | | | | |
|---|---|---|---|---|
| Count | 3 | 3 | 3 | 9 |
| Sum | 41 | 40 | 30 | 111 |
| Average | 13.66667 | 13.33333 | 10 | 12.33333 |
| Variance | 1.333333 | 6.333333 | 9 | 7.25 |

| *90* | | | | |
|---|---|---|---|---|
| Count | 3 | 3 | 3 | 9 |
| Sum | 33 | 37 | 27 | 97 |
| Average | 11 | 12.33333 | 9 | 10.77778 |
| Variance | 3 | 6.333333 | 4 | 5.444444 |

| *Total* | | | | |
|---|---|---|---|---|
| Count | 9 | 9 | 9 | |
| Sum | 131 | 132 | 91 | |
| Average | 14.55556 | 14.66667 | 10.11111 | |
| Variance | 16.77778 | 13.5 | 6.861111 | |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Sample | 141.5556 | 2 | 70.77778 | 10.00524 | 0.001198 | 3.554557 |
| Columns | 121.5556 | 2 | 60.77778 | 8.591623 | 0.002401 | 3.554557 |
| Interaction | 28.22222 | 4 | 7.055556 | 0.997382 | 0.434447 | 2.927744 |
| Within | 127.3333 | 18 | 7.074074 | | | |
| Total | 418.6667 | 26 | | | | |

**3.2.1** The two-way analysis of variance (ANOVA) as shown in tables 3.3 indicated that treatment duration had a statistically significant effect on the hardness of medium cashew nut shells ($F = 5.17$, $p = 0.0169$), whereas treatment temperature had no significant effect ($F = 2.11$, $p = 0.1507$) and the combine effect of treatment duration and temperature ($F = 0.189$, $p = 0.9412$) were not statistically significant at the 5% significance level which correspond to the findings of Adout *et al.*, (2012). These results indicated that the hardness of medium shells was primarily influenced by the duration of thermal exposure rather than by the treatment temperature within the investigated range of 200 - 300°C. Furthermore, the absence of a significant interaction suggests that the effect of heating duration remained consistent irrespective of the treatment temperature.

The mean hardness values demonstrated a progressive reduction with increasing treatment duration. The average hardness decreased from 30.00 at 30 min to 22.89N at 60 min, and further to 13.67N at 90 min, indicating that prolonged heating progressively weakened the shell structure. In contrast, the average hardness decreased from 26.89 at 200°C to 23.11N at 250°C and 16.56N at 300°C; however, these differences were not statistically significant because the variability within treatment groups exceeded the variation attributable to temperature. This finding suggests that although increasing temperature produced a downward trend in hardness, the magnitude of change was insufficient to establish a statistically significant independent temperature effect under the experimental conditions.

The significant influence of treatment duration observed in the present study is consistent with the general behaviour of lignocellulosic biomass during thermal pretreatment. Prolonged heating promotes the degradation of hemicellulose, disrupts hydrogen bonding within the cell wall, and initiates partial depolymerization of cellulose, thereby reducing the mechanical resistance of the material. Similar observations have been reported by Adeleke *et al*. (2022) and Boua *et al*. (2024), who found that extended thermal exposure progressively decreases the mechanical strength of agricultural residues through structural modification of the lignocellulosic matrix. The continuous decline in hardness with increasing residence time observed in the present study therefore reflects the cumulative effects of thermal degradation on the integrity of the shell structure.

Unlike several previous studies that identified temperature as the principal factor controlling the mechanical properties of thermally treated biomass according to Kocaefe, *et al*., (2008), the present investigation found that temperature did not significantly affect the hardness of medium cashew nut shells. This apparent discrepancy may be attributed to differences in biomass type, chemical composition, shell geometry, heating protocol, and the relatively narrow temperature range evaluated similar to the findings of Saracoglu and Coruh (2024). Medium cashew nut shells possess an intermediate thickness that may facilitate more uniform heat distribution while maintaining sufficient structural integrity to resist rapid thermal degradation (Chougule *et al*., 2025). Consequently, increasing the treatment temperature from 200°C to 300°C did not produce sufficiently large differences in hardness to reach statistical significance, whereas extending the heating duration allowed degradation reactions to accumulate over time, resulting in significant reductions in hardness.

The absence of a significant interaction between treatment duration and temperature further indicates that both factors acted independently throughout the thermal treatment process. This suggests that increasing the heating duration produced similar changes in hardness at all three temperatures, implying that residence time was the dominant processing parameter governing the mechanical response of medium cashew nut shells under the investigated conditions.

The findings demonstrated that treatment duration is the primary factor controlling the hardness of medium cashew nut shells, while treatment temperature exerts a comparatively smaller influence within the investigated range. The superior hardness retained by the medium shells throughout the experiment indicates greater resistance to thermal softening than the jumbo and small shell categories. From an engineering perspective, this enhanced thermal stability makes medium cashew nut shells particularly suitable for applications requiring high mechanical strength, including briquette production, composite reinforcement, and other biomass valorization processes where preservation of structural integrity is essential.

**Table 3.3**: Two-Factor ANOVA With Replication for Hardness of medium Cashew nut shells

| SUMMARY | 200 | 250 | 300 | Total |
|---|---|---|---|---|
| *30* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 97 | 95 | 78 | 270 |
| Average | 32.33333 | 31.66667 | 26 | 30 |
| Variance | 330.3333 | 302.3333 | 157 | 206.5 |
| *60* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 80 | 76 | 50 | 206 |
| Average | 26.66667 | 25.33333 | 16.66667 | 22.88889 |
| Variance | 58.33333 | 64.33333 | 64.33333 | 68.86111 |
| *90* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 65 | 37 | 21 | 123 |
| Average | 21.66667 | 12.33333 | 7 | 13.66667 |
| Variance | 44.33333 | 17.33333 | 13 | 60 |

| | *Total* | | |
|---|---|---|---|
| Count | 9 | 9 | 9 |
| Sum | 242 | 208 | 149 |
| Average | 26.88889 | 23.11111 | 16.55556 |
| Variance | 129.6111 | 168.8611 | 126.2778 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Sample | 1207.185 | 2 | 603.5926 | 5.167089 | 0.016852 | 3.554557 |
| Columns | 492.0741 | 2 | 246.037 | 2.106214 | 0.150691 | 3.554557 |
| Interaction | 88.14815 | 4 | 22.03704 | 0.188649 | 0.941234 | 2.927744 |
| Within | 2102.667 | 18 | 116.8148 | | | |
| Total | 3890.074 | 26 | | | | |

**3.2.2** The two-way analysis of variance (ANOVA) as shown in tables 3.4 bellow revealed that treatment temperature significantly influenced the hardness of small cashew nut shells ($F = 4.09$, $p = 0.0344$), whereas treatment duration does not ($F = 0.453$, $p = 0.6428$) and the interaction between treatment duration and temperature ($F = 1.434$, $p = 0.2634$) were not statistically significant at the 5% significance level. These results indicated that, unlike the jumbo and medium shells, the hardness of the small shells was governed primarily by treatment temperature rather than heating duration. Furthermore, the absence of a significant interaction demonstrated that the influence of temperature on hardness was independent of the duration of thermal treatment.

The mean hardness values showed that the average hardness increased from 9.67N at 200°C to 17.67N at 250°C, before remaining relatively unchanged at 17.44N at 300°C. In contrast, the average hardness varied only slightly with treatment duration, increasing from 13.56N at 30 min to 16.56N at 60 min, before decreasing marginally to 14.67N at 90 min. Although these variations suggest that prolonged heating produced some changes in hardness, the differences were not sufficiently large to establish statistical significance. The significant influence of temperature therefore indicated that thermal intensity was the dominant factor responsible for modifying the mechanical behaviour of the small cashew nut shells.

The increase in hardness observed between 200°C and 250°C may be attributed to the removal of free and bound moisture, together with the progressive consolidation of the shell structure resulting from moderate thermal modification. Moisture removal reduces the plasticizing effect of water within the lignocellulosic matrix, thereby increasing stiffness and resistance to indentation. As the treatment temperature approached 300°C, the hardness remained relatively stable, suggesting that the competing effects of structural densification and thermal degradation reached a balance within the investigated temperature range. This behaviour indicates that the small shells possessed sufficient thermal stability to maintain their mechanical integrity despite exposure to elevated temperatures.

The significant effect of temperature observed in the present study is consistent with previous investigations reporting that thermal intensity substantially modifies the mechanical properties of lignocellulosic biomass through alterations in chemical composition and cell-wall architecture. Moderate heating promotes moisture removal and increases structural rigidity, whereas excessive temperatures initiate degradation of hemicellulose and partial depolymerization of cellulose. The behaviour observed in the present study suggests that the temperature range investigated was sufficient to induce measurable structural modification in the small shells without causing extensive mechanical deterioration.

In contrast, treatment duration did not significantly affect hardness. This finding differs from the behaviour observed in the jumbo and medium shells, where prolonged heating produced significant reductions in hardness. The difference can be explained by the relatively smaller dimensions of the small shells, which promote rapid and uniform heat transfer throughout the material. Consequently, thermal equilibrium is attained more quickly, and extending the heating period beyond the initial exposure produces comparatively little additional modification of the lignocellulosic structure. Similar observations have been reported for finely divided lignocellulosic biomass, where reduced particle dimensions improve heat-transfer efficiency and minimize the influence of residence time on material properties.

The absence of a significant interaction between treatment duration and temperature further indicates that the effect of temperature remained essentially unchanged irrespective of heating duration. This demonstrates that the thermal response of the small shells was controlled predominantly by treatment temperature rather than by a combined or synergistic influence of both processing variables.

The findings demonstrated that treatment temperature is the principal factor governing the hardness of small cashew nut shells, while treatment duration has a comparatively limited influence within the investigated processing conditions. From an engineering perspective, the ability of the small shells to retain relatively high hardness at elevated temperatures suggests favourable thermal stability and indicates their potential suitability for thermally treated biomass applications where resistance to mechanical degradation is required. These results further demonstrate that the influence of thermal treatment on hardness is strongly dependent on shell size, emphasizing the need for shell-size-specific thermal pretreatment strategies to optimize the engineering performance of cashew nut shell biomass.

**Table 3.4**: Two-Factor ANOVA With Replicationfor
Hardness of small cashew nutshells

| SUMMARY | 200 | 250 | 300 | Total |
|---|---|---|---|---|
| *30* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 16 | 41 | 65 | 122 |
| Average | 5.333333 | 13.66667 | 21.66667 | 13.55556 |
| Variance | 2.333333 | 26.33333 | 49.33333 | 69.52778 |
| *60* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 40 | 55 | 54 | 149 |
| Average | 13.33333 | 18.33333 | 18 | 16.55556 |
| Variance | 36.33333 | 64.33333 | 81 | 51.27778 |
| *90* | | | | |
| Count | 3 | 3 | 3 | 9 |
| Sum | 31 | 63 | 38 | 132 |
| Average | 10.33333 | 21 | 12.66667 | 14.66667 |
| Variance | 32.33333 | 97 | 22.33333 | 61.5 |
| *Total* | | | | |
| Count | 9 | 9 | 9 | |
| Sum | 87 | 159 | 157 | |
| Average | 9.666667 | 17.66667 | 17.44444 | |
| Variance | 30 | 57.25 | 53.52778 | |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Sample | 41.40741 | 2 | 20.7037 | 0.452998 | 0.642771 | 3.554557 |
| Columns | 373.6296 | 2 | 186.8148 | 4.08752 | 0.034393 | 3.554557 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Interaction | 262.1481 | 4 | 65.53704 | 1.433955 | 0.263355 | 2.927744 |
| Within | 822.6667 | 18 | 45.7037 | | | |
| Total | 1499.852 | 26 | | | | |

***Note*:** Sample represents treatment duration, while columns stand as the treatment temperature and interaction is the combine effects of both treatment temperature and treatment duration, across all the tables

The three shell size categories exhibited distinctly different responses to thermal treatment, highlighting the importance of shell morphology in determining mechanical behaviour.

i. Both treatment time and temperature significantly reduced hardness of the jumbo shells, indicating greater susceptibility to prolonged heating and high thermal intensity.

ii. Hardness was influenced primarily by treatment time, while temperature produced no statistically significant effect for the medium shells.

iii. Temperature significantly affected hardness on the small cashew nut shells, whereas treatment time had little influence.

In all three shell sizes, the interaction between treatment time and temperature was not significant ($p > 0.05$). This indicates that the effects of these factors were additive rather than synergistic; the influence of one factor did not depend on the level of the other. Consequently, optimization of hardness can be achieved by controlling temperature and treatment duration independently rather than considering strong interactive effects.

From an engineering perspective, these findings demonstrated that shell size governs the thermal response of cashew nut shells. Larger shells experience greater internal thermal gradients and structural degradation under prolonged heating, whereas smaller shells respond more directly to temperature because of faster heat transfer. This size-dependent behaviour has important implications for designing thermal pretreatment processes for biomass conversion, briquette production, and biochar manufacture, where preservation or modification of mechanical properties is required.

### 3.3 Comparative behavior of the hardness of jumbo, medium and small cashew nut shells

The comparative evaluation of the three shell size categories demonstrated that shell size significantly influenced the response of hardness to thermal treatment. Although all shell categories were subjected to identical treatment temperatures and heating durations, their mechanical responses differed considerably, indicating that shell geometry and internal structure play important roles in determining thermal behaviour.

The jumbo shells exhibited significant effects of both treatment duration and temperature on hardness, indicating that their relatively thicker shell walls were sensitive to both thermal intensity and prolonged heating. The reduction in hardness observed at higher temperatures and longer treatment durations suggests that larger shells experienced greater internal thermal gradients, which promoted progressive degradation of the lignocellulosic matrix and consequently reduced resistance to indentation.

In contrast, the medium shells showed a significant effect of treatment duration but not treatment temperature. This behaviour indicates that the medium shells possessed greater thermal stability than the jumbo shells within the investigated temperature range. Their intermediate shell thickness likely facilitated more uniform heat distribution while maintaining sufficient structural integrity to resist rapid thermal degradation. Consequently, prolonged heating rather than thermal intensity became the principal factor governing hardness reduction.

The response of the small shells differed markedly from those of the jumbo and medium shells. Temperature significantly influenced hardness, whereas treatment duration did not. The smaller shell dimensions likely promoted rapid heat penetration and shorter equilibration times, thereby reducing the influence of residence time. Without significantly degrading the lignocellulosic framework, moderate heating improved moisture removal and structural consolidation, leading to higher hardness.

A comparison of the mean hardness values revealed that, under most treatment settings, jumbo shells had the lowest hardness, while medium shells consistently showed the maximum hardness, followed by small shells. The medium shells' greater mechanical performance indicates that their structural composition and shell thickness are better balanced, allowing them to tolerate heat treatment without significantly losing hardness.

The findings showed that shell size has a significant impact on how thermal treatment affects hardness. The observed discrepancies are explained by differences in the lignocellulosic matrix's thermal stability, moisture migration, heat-transfer properties, and shell thickness. These results suggested that shell-size-specific processing conditions are necessary to optimize mechanical performance and enhance the use of cashew nut shells in biomass engineering applications, as a single thermal pretreatment condition might not be suitable for all shell sizes.

## 4. Conclusion and Recommendations

This comparative study evaluated the influence of thermal treatment temperature (200, 250, and 300°C) and heating duration (30, 60, and 90 min) on the hardness of jumbo, medium, and small cashew nut shells. The statistical analysis revealed that heating duration consistently exerted a significant effect on hardness across all three shell size categories, whereas treatment temperature did not produce a statistically significant independent effect within the investigated range. Furthermore, the absence of significant interaction between treatment duration and temperature confirmed that these factors operated additively rather than synergistically across all shell sizes. Notably, the three shell categories exhibited distinctly different hardness responses to thermal treatment: jumbo shells were susceptible to both prolonged heating and elevated temperature; medium shells were influenced primarily by heating duration, with temperature exerting no significant effect; and small shells were governed predominantly by temperature, with duration playing a limited role. These size-dependent differences are attributed to variations in shell thickness, heat-transfer characteristics, and the thermal stability of the lignocellulosic matrix.

Among the three categories, medium cashew nut shells consistently exhibited the highest hardness values across all treatment conditions, demonstrating superior resistance to thermal softening compared with jumbo and small shells. The medium shells also maintained relatively high hardness at 250°C for 30 min, suggesting a practical compromise where additional thermal modification is desirable without substantial loss of mechanical strength. From an engineering perspective, the findings establish that treatment duration is the dominant processing parameter governing the hardness of thermally treated cashew nut shells, and that shell-size-specific pretreatment strategies are necessary for optimal performance in biomass conversion applications. The superior mechanical properties of medium-sized shells make them the most suitable feedstock for engineering applications requiring high mechanical strength, including briquette production, composite reinforcement, and other biomass valorization processes.

This study contributes to the growing body of knowledge on the valorization of agricultural residues within the circular bio-economy framework, supporting the development of efficient and sustainable biomass conversion technologies. The findings also highlight the importance of considering morphological variations in biomass feedstocks when designing thermal pretreatment processes, a factor often overlooked in studies that treat agricultural residues as homogeneous materials.

### 4.1 Recommendations

i. Thermal pretreatment of cashew nut shells should be carried out for 30–60 minutes to preserve hardness and structural integrity.
ii. Medium-sized shells are recommended for applications requiring high mechanical strength, such as briquette production and composite reinforcement.
iii. Further studies should investigate the microstructural and chemical changes responsible for hardness variation using techniques such as SEM and FTIR.
iv. Pilot-scale studies are recommended to validate the optimum thermal treatment conditions for industrial utilization of cashew nut shells.

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