

Modeling the Effect of Thermal Treatment on Hardness of Medium Cashew Nut Shells

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Abstract: Thermal processing has become an important pathway for mechanical modification of agricultural by-products for value addition and sustainable utilization. Cashew nut shell, an abundant lignocellulosic residue in Nigeria, possesses engineering properties that can be modified through controlled thermal treatment. This study investigated the resulting impact of temperature and time interactions on the hardness of medium cashew nut shell accessions and established an empirical model using the Buckingham Pi theorem. Medium cashew nut shells sourced from the Cocoa Research Institute of Nigeria (CRIN) were subjected to thermal treated at 200, 250, and 300°C for 30, 60, and 90 mins. The hardness and compressive strength were determined using a universal testing machine (UTM), while the physical and thermal properties including density; moisture content, thermal conductivity, and specific heat capacity were determined using standard engineering methods. Dimensional analysis was used to establish dimensionless π -terms, which formed the prediction equation for hardness: $H = \Phi \left(\frac{\rho \theta K}{T \sigma} \right)$. The generalized reduced gradient (GRG) nonlinear Excel solver was used to estimate the model constant (Φ) in order to minimize the sum of squared errors. The model's predictive capacity was confirmed by validation, with a low RMSE of 0.86 and a high RPD of 28.6, indicating an excellent predictive capacity. The outcome showed that shell hardness is significantly changed by thermal treatment, and the devised model successfully accounts for these changes. This technique has potential for improving thermal processing in agro-industrial applications such as cashew shell valuation.

Keywords: Buckingham Pi theorem, cashew nut shell, GRG nonlinear optimization, predictive modeling, thermal treatment, thermo-mechanical properties

1. Introduction

Cashew nut (*Anacardium occidentale* L.) remains one of the fastest-growing tree nut commodities globally, with world production exceeding 3.9 million metric tons in 2023 and continuing to rise into 2024 due to expanding African and Asian processing capacity (FAO, 2024). Nigeria remains a significant producer in Africa, supported by export-oriented incentives and expanding local processing initiatives (UNCTAD, 2023). This growth has led to a proportional increase in cashew nut shell (CNS) generation, as the shell constitutes approximately 50 – 60% of the whole nut mass (Food and Agriculture Organization, 2023; International Nut and Dried Fruit Council, 2022; Central Food Technological Research Institute, 2019).

Large volumes of CNS are now produced annually as a result of growing domestic processing in Africa between 2022 and 2025, raising both industrial and environmental problems. Shells are still underutilized in many industrial clusters, where they are frequently burned in the open or burned inefficiently to produce heat. Because of the phenolic-rich cashew nut shell liquid (CNSL) present in the shell matrix, these techniques lead to energy losses and environmental emissions (Mazzetto et al. 2009; FAO, 2024). Agricultural leftovers like CNS are receiving more attention due to the recent global emphasis on biomass valorization, renewable energy transition, and the circular bio-economy (IEA, 2023; UNCTAD, 2023). Because of their high calorific value and lignocellulosic content, cashew nut shells can be used in briquetting, the creation of activated carbon, the production of pyrolysis oil, and thermochemical energy conversion (Silva et al. 2016; Adeyanju et al. 2021). However, the mechanical, physical, and thermal characteristics of the material have a significant impact on these applications' sustainability and efficiency.

Research revealed that CNS properties, including as moisture behavior, density, compressive strength, thermal conductivity, and volatile matter composition, are considerably changed by controlled heat treatment (Adeyanju et al. 2021; Agunbiade and Akinoso, 2023). Energy yield, handling qualities, and structural integrity are all impacted by temperature-time interactions. Despite these advancements, little is known about how controlled heat regimes consistently alter the technical characteristics of CNS, especially in African production environments and among various shell sizes or types.

It is imperative to maximize CNS usage through scientific modeling of property changes under regulated heat treatment, given the ongoing growth of cashew processing in Nigeria and other African nations as of 2026. This information will strengthen the sustainability of the cashew value chain, improve energy efficiency, lessen environmental pollution, and promote industrial development based on biomass. Despite their potential, cashew nut shells are usually misused and thrown away as garbage in Nigeria.

However, according to Kadjo *et al.* (2024), recent research has demonstrated that cashew nut shells' mechanical, physical, and thermal qualities can be enhanced with appropriate thermal treatment, increasing their potential for industrial uses. Nigerian cashews, particularly the jumbo, medium, and small accessions, each have distinct qualities that may determine how heat treatments impact their features (CRIN, 2021). Cashew nut shells' strength, hardness, moisture content, density, heat capacity, thermal conductivity, and other important characteristics may be changed by thermal processes like roasting or pyrolysis. Examining these impacts is essential to figuring out how to make cashew nut shells more useful in a variety of commercial and industrial uses, particularly in the fields of bioenergy and material engineering (Kadjo *et al.* 2024).

Materials and Methods

1.1 Description of Study Area

Samples of cashew nuts were obtained from the Cocoa Research Institute of Nigeria (CRIN) cashew germplasm, which is situated in the Oluyole Local Government Area of Ibadan, Oyo State, km 14 Adebayo along the Ijebu/Ode Express Road, Ibadan (Latitude 07°10' N, Longitude 03°52' E), with bimodal rainfall (CRIN, 2022; Oyo State Government, 2021).

2.2 Materials and Equipment

The materials and equipment's used in this research were:

- i. Cashew nut shells
- ii. Universal Testing Machine
- iii. Stop watch
- iv. Weighing balance
- v. Vernier caliper
- vi. Sample nylons and Gloves
- vii. Distilled water
- ix. Thermometer

2.3 Samples Preparation

After being obtained from the cashew germplasm of the Cocoa Research Institute of Nigeria (CRIN), located in Ibadan, Nigeria, cashew nut shells were cleaned to get rid of any foreign materials that might stick to them. They were then divided into three size categories: jumbo, medium, and small, according to predetermined mass ranges and were measured using a digital analytical balance (± 0.01 g). The jumbo shells weighed ≥ 16 g and the medium shells weighed $\geq 6 - 8$ g, while the small shells weighed $\geq 2 - 6$ g, 3,000 samples of the medium cashew nut were labeled and stored under ambient laboratory conditions prior to further analysis.

2.4 Shaping

Samples were cut into two distinct parts using a manually operated cashew nut cracker in microbiology lab of cocoa research institute of Nigeria for mechanical, physical, and thermal properties testing as shown in Plate 3.1.



Plate 2.1: Manual cashew nut cracker

2.5 Drying

Samples were oven-dried at 105 °C for 4 h to remove moisture and standardize initial conditions as shown in Plate 2.2 (Oladipo, 2011).



Plate 2.2: Drying of jumbo cashew nut shells

2.6 Thermal treatment

The medium cashew nut shells were subjected to varying thermal treatment temperatures (200, 250, and 300 °C) at durations of (30, 60, and 90 mins respectively) in an oven. As shown in Plate 2.3



Plate 2.3: thermal treatment of medium cashew nut shells at 200, 250, and 300°C for 30, 60, and 90 minutes respectively

2.7 Laboratory Procedures

The mechanical and physical property tests were carried out using standard laboratory procedures in the Department of Agricultural Engineering Laboratory at the National Centre for Agricultural Mechanization (NCAM), Ilorin. Prior to testing, samples were cleaned, conditioned to room temperature, and appropriately labeled accordingly. Vernier caliper was used to measure the sample's initial dimensions (length, width, and thickness) before and after treatment, the Universal Testing Machine (UTM) was used to measure compressive strength and hardness. Each sample was then positioned centrally between the UTM's compression platens and subjected to progressively increasing compressive load at a consistent rate, until failure or occurred, and the highest load at failure was recorded.

The greatest force divided by the sample's cross-sectional area was used to determine compressive strength. Using the UTM, the sample was placed on the hardness testing platform, the proper indenter was fitted when needed, and compressive force was applied gradually until permanent deformation or failure occurred. The associated load was recorded as the hardness value. Using the mass-volume relationship, the density was calculated by dividing the mass by the volume after the sample mass was measured with a digital weighing balance and the volume was calculated using a geometric approximation of the shell shape. To ascertain mean values and variability among treatments and cashew nut shells, all collected data was documented and statistically analyzed

2.8 Experimental Design

A completely randomized design (CRD) set up in a 3^3 factorial experiment was used. Compressive strength, hardness, density, thermal conductivity, and heat capacity were the dependent variables and thermal treatment temperature (200, 250, and 300 °C), and treatment duration (30, 60, and 90 min), as well as the shell size (medium) were the independent variables. To provide sufficient sample size and statistical reliability for the assessment of the engineering and thermal properties, a total of 3000 medium cashew nut shells were employed, and each treatment combination was replicated three times.

2.9 Determination of mechanical properties of medium cashew nut shells

A hydraulic universal testing machine (UTM), model CPS 150 kN (15-ton capacity), produced by Fine Tech Indian OEM in an ISO 9001-certified facility, was used to determine the mechanical parameters, the parameters include; compressive strength and hardness. According to ISO 7500-1 Class 1 requirements, the machine runs with a displacement accuracy of $\pm 0.5\%$ and a load measurement accuracy of $\pm 1\%$. During mechanical testing, it can precisely manage the loading rate because to its variable crosshead speed, which ranges from 0 to 500 mm min^{-1} . To guarantee accuracy, reproducibility, and international conformity, all tests were carried out in conformance with applicable ASTM and ISO standards for mechanical property evaluation. Plate 3.3 shows the universal testing machine's experimental setup. As seen in Plates 3.4 and 3.5, a UTM was used to measure the compressive strength and hardness of treated medium cashew nut shells. The samples were positioned one after the other between two flat plates, the UTM applied a progressively increasing compressive load, and the machine recorded the maximum force applied before the sample failed, the compressive strength was recorded as force at peak, and the hardness was recorded as force at break. The results were shown on a digital control panel.



Plate 2.4: Universal Testing Machine (UTM)

2.10 Determination of compressive strength and hardness of medium cashew nut shells

The highest compressive stress a material can sustain before failing is known as its compressive strength. UTM was used to determine the compressive strength as seen in Plate 2.5; the treated samples underwent axial compression using a UTM. The highest load before failure was noted. Using UTM as the force at breaking point, the hardness of the treated medium cashew nut shells was assessed as indicated in plate 2.5; samples were axially compressed using a UTM. The UTM's is connected to a screen where results of the compressive strength and hardness are displayed.



Plate 2.5: Determination of compressive strength and hardness of medium cashew nut shells

2.11 Determination of physical properties of medium cashew nut shell

Density, moisture content, and shrinkage are among the physical characteristics that were identified. The dimensions of the cashew nut shells were measured using a Vernier caliper, a 0–150 mm x 0.02 mm stainless steel under ISO 9001 standard with $\pm 0.03\text{mm}$ accuracy in compliance with DIN 862. With a maximum capacity of 500g x 0.01g resolution, $\pm 0.02\text{g}$ accuracy, three 2 A batteries, auto calibration, tare, and overload protection features, this small electronic precision weighing balance is made by a Chinese OEM and is usually ISO 9001.

2.12 Determination of density of medium cashew nut shell

The density of the cashew nut shell was determined using the method described by Callister *et al.* (2018): density was calculated using Equation (2.1)

Volume of the cashew nut shell was determined using the displacement method

$$\rho = \frac{M}{V} \quad 2.1$$

Where,

$$\rho = \text{Density (g/cm}^3\text{)}$$

$$M = \text{Mass (g)}$$

$$V = \text{Volume (cm}^3\text{)}$$

2.13 Determination of moisture content of medium cashew nut shell

Moisture content refers to the amount or proportion of water present in a material or substance, typically expressed as a percentage of the materials total weight or dry weight. Moisture content (%) was calculated using Equation 2.2 as described by Akinmoladun *et al.* (2019)

$$\text{Moisture Content} = \frac{W_i - W_d}{W_i} \times 100 \quad 2.2$$

Where,

W_i and W_d is initial and dry weight of the cashew nut shells in grams

2.14 Determination of thermal properties of medium cashew nut shell

Predicting the behavior of heat transmission during thermal processing procedures depends heavily on the thermal characteristics of cashew nut shells. In this study, validated empirical correlations provided by Bart-Plange *et al.* (2012) and Singh and Heldman (2014) were used to determine thermal conductivity (k) and specific heat capacity (Cp) of the medium cashew nut shell. By expressing thermal qualities as variables of quantifiable physical parameters like temperature, bulk density, and moisture content, these correlations allow for indirect evaluation without the need for direct calorimetric or transient heat-flow measurements.

Several underlying presumptions served as the foundation for the implementation of these empirical models. It was hypothesized that the medium cashew nut shell matrix behaved as a homogeneous, isotropic lignocellulosic solid, suggesting that the thermal transport properties had very little directional dependency. At the time of measurement, it was assumed that each sample had a homogeneous moisture distribution with no internal gradients. Thermo-physical parameters were supposed to vary smoothly with temperature within the validated range of the original models, and heat transport was thought to occur under steady state or quasi-stationary circumstances. Furthermore, the correlations implicitly assume that only physical changes (primarily moisture removal) occur, and that no significant chemical decomposition, phase transformation, or structural collapse alters the intrinsic thermal transport mechanisms within the prediction range (Di Blasi, 2008).

2.15 Determination of thermal conductivity of medium cashew nut shell

The rate at which a product transmits heat is known as its thermal conductivity, and it was determined using Equations 2.3 and 2.4. A 25mm-long probe was submerged in the mass of medium cashew nut shell samples with a constant current of 1A and a voltage that varied from 2.04 to 6.68 volts, respectively. The voltage variation was caused by changes in temperature and an increase in load.

$$k = \frac{Q \ln(t_1/t_2)}{4\pi(T_2 - T_1)} \quad 2.3$$

Where,

k is the thermal conductivity (W/m.K)

Q is the heat input rate per unit length

$$Q = \frac{VI}{L} \quad 2.4$$

V = Electrical voltage (v)

I = Electric current (A)

L = Probe Length (m)

$\ln \frac{t_1}{t_2}$ = Logarithm of time ratio

t_1 and t_2 = Initial time and final time

T_1, T_2 = Final and initial temperature

2.16 Determination of specific heat capacity of medium cashew nut shell

The quantity of heat needed to raise a product's temperature by one degree Celsius is known as its heat capacity, and it was calculated using Singh and Heldman's equation (2014). Samples of medium cashew nut shells were oven-dried at 105 °C to constant weight in order to evaluate their moisture content for further treatment at the intended temperature and time. The wet-basis moisture fraction was computed by dividing the mass of water by the mass of the initial wet sample. The equation outlined by Singh and Heldman (2014) was used to estimate the specific heat capacity of medium cashew nut shells.

$$\text{Specific heat capacity}(c) = 0.837 + 3.348M \quad 2.5$$

M is the moisture content of the samples

3 Development of predictive model using buckingham pi theorem

Models are instruments that replicate nature by incorporating empirical knowledge in ways that permit quantitative conclusions to be formed from them. Additionally, it is a tool that uses initial conditions, boundary conditions, and a set of rules to forecast a system's future state (Ndirika, 2019). To model the relationship between thermal treatment parameters and cashew nut shell qualities, dimensionless groups were created using the Buckingham Pi theorem. The technique involves the following steps,

i Dimensional analysis: the numerical value of any quantity is in a mathematical model which is measured with respect to a system of unit (for example, meters in mechanical model).

ii Scaling denotes a fundamental system of units such as (M, L, T) in mechanics and a quantity that is measured in respect to the system (Hunter, 2009) as shown in Tables 3.1 and 3.2.

iii Non-dimensionalization: scale-invariance implies that we can reduce the number of quantities appearing in a problem by introducing dimensionless quantities.

3.1 Identifying variables

- A. Independent variables:
- Temperature (T),
 - Duration (t)
- B. Dependent variable:
- Compressive strength
 - Hardness
 - Density
 - Thermal conductivity
 - Specific heat capacity

3.2 Dimensional analysis

The variables were expressed in terms of fundamental dimensions (M, L, T). Table 3.1 represents the summary of dimensions of the variables considered and Table 3.2 represents the dimensional matrix of the fundamental variables.

Table 3.1: Dimensions of the variables

Variables	Symbol	Dimensions (M, L, T)
Stress	σ	$ML^{-1}T^{-2}$
Hardness	H	$ML^{-1}T^{-2}$
Density	ρ	ML^{-3}
Thermal Conductivity	k	$MLT^{-3}\theta^{-1}$
Specific Heat Capacity	C_p	$L^2T^{-2}\theta^{-1}$
Temperature	T	θ
Time	t	T

Table 3.2: Dimensional matrix of the variables

Dimensions	Parameters						
	σ	H	ρ	k	C_p	T	θ
M	1	1	1	1	0	0	0
L	-1	-1	-3	1	2	0	0
T	-2	-2	0	-3	-2	1	0
θ	0	0	0	-1	-1	0	1

The dimensionless groups for modeling the relationship between thermal treatment parameters and cashew nut shell properties were derived using the Buckingham Pi theorem. In this study, the primary response variable considered for modeling and validation was hardness, while the independent variables included thermal treatment temperature, treatment duration, and shell size.

According to the Buckingham Pi theorem, a set of dimensionless π -groups can be expressed as: $\pi_1 = f(\pi_2, \pi_3 \dots \dots \pi_n)$.

Where π_1 represents the dimensionless group containing the dependent variable (hardness), $(\pi_2, \pi_3 \dots \dots \pi_n)$ correspond to groups formed from combinations of the independent variables and fundamental dimensions (mass, length, time, temperature). The π -groups were systematically constructed by selecting repeating variables that capture the dominant physical influences on shell hardness while ensuring dimensional homogeneity across the model. The use of π -groups enables optimization of thermal treatment conditions for engineering purposes, such as maximizing hardness while minimizing energy input or structural degradation.

Total number of variables (n) from table 3.1 is 7; number of fundamental dimensions (m) from table 3.2 is 4

$$\pi_{terms} = n - m \rightarrow \pi_{terms} = 7 - 4 = 3$$

$$\theta, T \propto f(\sigma, H, \rho, K, C_p) \quad 2.6$$

$\pi_1 = \phi f(\pi_2, \pi_3)$ With regards to the total number of Pi groups to be formed

$$\phi = \frac{\pi_1}{(\pi_2, \pi_3)} \quad 2.7$$

Where, $\emptyset$ = constant temperature

$$\pi_1 = [\theta]^{C1} \cdot [\sigma]^{C2} \cdot [H]^{C3} \cdot [\rho]^{C4} \cdot [K]^{C5} \cdot [C_p]^{C6} \cdot [T]^{C7} \quad 2.8$$

By expanding 2.8 you obtain the following equations bellow to compute π_1, π_2 , and π_3 respectively.

Comparing the powers,

$$M: C2 + C3 + C4 + C5 = 0$$

$$L: -C2 - C3 - 3C4 + C5 + 2C6 = 0$$

$$T: -2C2 - 2C3 - 3C5 - 2C6 + C7 = 0$$

$$\theta: C1 - C5 - C6 = 0$$

To obtain π_1 ,

Assuming an arbitrary values for $C1 = 1, C2 = 0, C3 = 0$ (Ndirika, 2019)

$$\pi_1 = \frac{\theta \rho T C_p^2}{K} \quad 2.9$$

To obtain π_2 ,

Assume arbitrary values for $C1 = 0, C2 = 1, C3 = 0$ (Ndirika, 2019)

$$\pi_2 = \frac{\sigma \rho T C_p^2}{K} \quad 2.10$$

To obtain π_3 ,

Assume arbitrary values for $C1 = 0, C2 = 0, C3 = 1$ (Ndirika, 2019)

$$\pi_3 = \frac{\sigma \rho T C_p^2}{K} \quad 2.11$$

Substituting 2.9, 2.10 and 2.11 in 2.7 to obtain 2.12 which is the general model

$$\pi = \left[\frac{(\sigma \rho T C_p^2)^{-I}}{(\sigma \rho T C_p^2)^{-I} \times (\sigma \rho T C_p^2)^{-I}} \right] \quad 2.12$$

Linearize Equation 2.12 using the least square method to obtain the model of the hardness of the medium cashew nut shell as shown in Equation 2.13

$$\pi = \pi \left(\frac{\sigma \rho T C_p^2}{K} \right) \quad 2.13$$

3.3 Establishment of model constant

The model constant that was used to estimate the expected hardness of the medium cashew nut shells for various combinations of operating circumstances in Equations 2.13 and experimental results, respectively, was established using the generalized reduced gradient (GRG) nonlinear Excel solver. This is comparable to Ekemube *et al.*, (2022a, 2022b, 2023) and Jimeshio, *et al.*, (2025) model of fuel consumption during plowing, harrowing, and ridging operations and modeling the effect of thermal treatment on the hardness of small cashew nut shells, which was created using the Buckingham pi theorem and used GRG to build constants. In its most basic form, GRG is a solver method that looks at the objective function's gradient or slope as the input values or decision variables change. When the partial derivatives equal zero, it is said to have obtained an optimal solution.

3.4 Validation of the model

In accordance with the validation criteria suggested in engineering modeling literature, model performance was assessed using RMSE and RPD (Kadjo *et al.* 2024; Jimeshio *et al.*, 2025). By applying the generated model to forecast hardness (H) and comparing the model's output with the experimental data, the model was validated. The residual prediction deviation Equation 3.6 and the root-mean-square-error (RMSE) Equation 3.5 were used to assess the model's predictive capacity.

$$\text{RMSE} = \sqrt{\sum_{i=1}^n \frac{(\hat{Y}_i - Y_i)^2}{n}} \quad 3.5$$

where,

n = number of samples

$\hat{Y}_i$ = predicted ith values,

Y_i = measured ith values

$$\text{RPD} = \frac{\text{SD}}{\text{RMSE}} \quad 3.6$$

Where:

SD = standard deviation of the measured experimental data.

Model prediction ability was described as excellent if $\text{RPD} > 2.0$, and almost good if $1.4 < \text{RPD} < 2.0$, and unreliable if $\text{RPD} < 1.4$ Chang *et al.*, (2001)

4 Results and Discussion

4.1 Development and validation of the predictive model on the effect of thermal treatment on the hardness of cashew nut shells

The predictive model developed using the Buckingham Pi theorem on the effect of thermal treatment on hardness of jumbo cashew nut shells is shown in Equation 4.1

$$H = K \left(\frac{\rho T}{K} \right)^{0.28} \quad 4.1$$

Equation 4.1, which combines intrinsic material qualities and thermal processing factors into a single thermo-mechanical framework, expressed the hardness (H) of cashew nut shells as a function of the dimensionless ratio. Due to increased structural compactness, improved heat penetration, and thermo-induced consolidation of the lignocellulosic matrix, the cashew nut shells' hardness increased with increasing density, treatment temperature, and thermal conductivity. However, the hardness response is moderated by longer heating times and higher inherent compressive strength because excessive heat exposure promotes structural degradation and higher compressive resistance may limit relative modification. Thus, Equation 4.1 demonstrated that temperature and heating time primarily controls the intensity of structural transformation, and their interaction determines the optimum hardness condition before thermo-degradation becomes dominant.

Measured and anticipated findings, including error squared, are displayed in Tables 4.1 to 4.3. The relationships between temperature, time, and specific technical qualities were well-described by the predictive models created utilizing the Buckingham Pi theorem as in Equation 4.1. The models' dependability was validated by the observed low sum of squared errors (SSE = 6.369857). Excellent predictive capacity was indicated by residual prediction deviation (RPD) values above 20 and low root mean square error (RMSE) values (0.28), as shown in Table 4.4 (Chang et al. 2001).

The jumbo cashew nut shell showed a high RPD of 34.79 which suggested a stable model response. The Buckingham Pi-based model's validity and applicability for extrapolating the impact of heat treatment on cashew nut shells are supported by this remarkable connection between experimental and predicted values. Ekemube *et al.*, (2023) found similar modeling success when they applied the Buckingham theorem to create a tractor fuel consumption model utilizing GRG nonlinear optimization techniques.

Table 4.1: Effect of thermal treatment on the hardness of jumbo cashew nut shells

ρ	ρ , g/cm ³	ρ , [°]	K, W/m.k	ρ , [°]	T, min	H (Measured) N	H (Predicted) N	Error ²
3716.745	0.972	200	0.142	60	30	57	57	2.02E-28
3716.745	0.981	200	0.128	39	60	41	39.88925	1.233765
3716.745	0.882	200	0.122	27	90	33	32.91659	0.006957
3716.745	0.934	250	0.134	70	30	55	55.37773	0.142679
3716.745	0.875	250	0.117	39	60	40	40.6519	0.42497
3716.745	0.967	250	0.113	31	90	37	36.3918	0.369913
3716.745	0.77	300	0.122	97	30	34	35.99495	3.979826
3716.745	0.775	300	0.114	53	60	31	30.97872	0.000453
3716.745	0.725	300	0.107	35	90	27	27.45967	0.211292

SSE = 6.369857

Table 4.2: Result of the Model Validation Tools

S/No.	Validation Tools	Jumbo
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1	RMSE	0.280429
2	RPD	34.78783

5. CONCLUSION

The Buckingham Pi theorem developed using dimensional analysis was used in this study to simulate how thermal treatment impacted the hardness of medium cashew nut shells. Large RPD values and low RMSE indicated that the predictive model successfully captured these relationships. According to these results, thermally treated medium cashew nut shells have potential as sustainable raw materials for thermal insulation, composite reinforcement, and energy production in engineering.

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