

Thermochemical Conversion of Cashew Nutshell Through Slow Pyrolysis: Process Optimization and Product Yield Analysis using Response Surface Methodology

¹*Oniya, O. O., ²Nasirudeen, A. R., ¹Ola, F. A., ¹Oyekunle, Y. Y. and ³Omoyeni, O. D.

¹Department of Agricultural Engineering, Ladoko Akintola University Technology, Ogbomosho, Oyo State, Nigeria.

²Department of Agricultural and Bio-Environmental Engineering, Oyo State College of Agriculture and Technology, Igboora, Nigeria.

³Department of Agricultural and Bio-Resources Engineering, Federal University Oye Ekiti, Ekiti State, Nigeria.

*Corresponding Author E-mail: arnasirudeen@oyscatech.edu.ng Tel : +2348063894989

Abstract

This study investigated the slow pyrolysis of cashew nutshell (CNS) to evaluate the effects of heating temperature (300–700 °C) and holding time (20–100 min) on product yields (biochar, bio-oil, and syngas). Using a Central Composite Design through Response Surface Methodology (RSM), experiments were conducted on cleaned and sun-dried CNS sourced from Oyo State, Nigeria. Experimental data were statistically analyzed using Analysis of Variance (ANOVA) at a 95 % confidence level. Under the experimentally tested pyrolysis conditions, yields ranged from 42–72 % for biochar, 6–29 % for bio-oil, and 22–36 % for syngas. The quadratic models for biochar and syngas were statistically significant ($P \leq 0.05$) with R^2 values of 0.9487 and 0.9474, respectively. The bio-oil model exhibited a lower fit ($R^2 = 0.49$), indicating that liquid yield is influenced by factors beyond the tested variables. These findings establish a reliable framework for understanding the thermochemical valorization of cashew nutshell residues, highlighting heating temperature as the dominant factor governing product distribution.

Keywords: Lignocellulosic biomass, Response Surface Methodology, slow pyrolysis, optimization biochar yield, bio-oil, syngas, heating temperature, holding time.

Introduction

The management of agricultural residues is a major concern in today's society, as most residues are burnt, chemically treated, dumped into waterways, or buried in landfills. Approximately forty percent of agricultural garbage is simply dumped with no further processing (FAO, 2023). Poor residue disposal is hazardous to human health and the environment because it pollutes the air, water, and soil and facilitates disease transmission (Kosre *et al.*, 2021). Cashew (*Anacardium occidentale* L.) is a tropical tree native to Northeastern Brazil, now widely cultivated in regions with suitable climates across the globe. Nigeria is one of the leading producers of cashew nuts in the world, producing about 240,000 – 250,000 metric tonnes per annum, projected to increase to 300,000 metric tonnes by 2030. This contributes significantly to the global cashew market, driven by increasing demand both locally and internationally (Efetebor *et al.*, 2022). The economic significance of cashew lies primarily in its kernel, which is consumed worldwide as a popular snack and culinary ingredient. However, the processing of cashew nuts generates a substantial amount of residue in the form of cashew pod husks, referred to as cashew nutshell (CNS). The nutshell consists of the outer shell (husk or pericarp) which encloses the kernel. After harvesting, the kernels are extracted, leaving behind the nutshells which constitute about 35-50 % of the total weight of the cashew fruit. These nutshells are typically discarded through open burning or left to decompose, leading to environmental pollution and wasted potential resources (Raju *et al.*, 2012).

Pyrolysis, a thermochemical decomposition process conducted in the absence of air, offers a transformative pathway for the conversion of lignocellulosic biomass into value-added biomaterials: biochar (carbon-rich solid product), bio-oil (liquid fuel precursor) and syngas (gaseous energy carrier). It is considered one of the most uncomplicated and effective thermal conversion processes (Bridgwater, 2012). However, specific

research on cashew nutshell residue pyrolysis remains limited, highlighting a significant gap in current knowledge. Understanding the chemical composition and thermochemical behavior of cashew nutshell residues is crucial for optimizing pyrolysis process parameters. This study seeks to address these gaps by exploring the potential of CNS as a feedstock for slow pyrolysis to produce biochar, bio-oil, and syngas. By converting these residues into valuable bio-based products, this research aims to contribute to sustainable waste management practices, reduce environmental pollution from agricultural residues and explore new avenues for renewable energy applications.

Materials and Methods

The cashew nutshells were collected from Global Confluence Nigeria Limited, Iseyin, Oyo State, Nigeria with a geographical location (7.9765° North, 3.5914° East). The collected nutshells were manually cleaned and sorted to separate immature shells, stalks, leaves and other impurities. The initial moisture content of the feedstock was determined using the oven-drying procedure of the ASTM E871-80 standard method. Sample weights of about 10 g were oven-dried at 105 °C until a constant weight was obtained. Thereafter, the cleaned shells were sun-dried for 7 to 10 days to reduce the moisture content to a safe storage level of about 10-12 %. The cleaned and sun-dried cashew nutshell as in Plate 1a, was then milled and sieved into 2 mm sample sizes as shown in Plate 1b for the pyrolysis process.

Experimental setup

A fixed-bed, batch pyrolysis equipment was used in this experiment. The equipment consists of a cylindrical reactor/retort, an electric heating furnace, a condensate receiver, an ice-cooling unit, and a gas collection unit. During the experiment, the retort, after being loaded with the desired quantity of ground sample material, was sealed and placed into the furnace. The retort was connected through piping to the condensate receiver, which was placed in an ice-cooling unit for the recovery of condensable products (bio-oil/tar). The condensate receiver was subsequently connected to the gas collection unit for the recovery of uncondensed gases (syngas).



(a)



(b)

Plate 1: Samples: (a) Cleaned and sun dried cashew nutshell; (b) Milled cashew nutshell

Pyrolysis experimental design

The Central Composite Design (CCD) of the Response Surface Methodology (RSM) was used for optimization and fitting quadratic models. The tests were carried out with three responses (biochar, bio-oil and syngas yields) and two operating parameters (heating temperature and holding time), each considered at five levels: $-\alpha$, -1 , 0 , $+1$, and $+\alpha$. For this study, the number of operating parameters $n = 2$, yielding an

alpha value (α) of 1.414. The actual experimental ranges and levels are presented in Table 1. The total number of experimental runs (N) was calculated as: $N = 2^k + 2k + n_c = 2^2 + 2(2) + 8 = 16$ runs where k is the number of parameters and n_c is the number of center point replicates. The adequacy of the models was evaluated using the coefficient of determination (R^2), adjusted R^2 , predicted R^2 , adequate precision, F-value and p-values. A significance level of 0.05 was used. Analysis of Variance (ANOVA) was conducted to evaluate model significance and lack of fit. Diagnostic checks, including residual analysis, were performed to verify model adequacy.

Table 1: Experimental Range and Levels of Process Variable Codes

Parameter	-1.412	-1	0	+1	+1.412
Heating temperature, °C	300	400	500	600	700
Holding time, min	20	40	60	80	100

Experimental procedure of pyrolysis

For each pyrolysis runs, known weight (100 g) of the desired sample material was placed inside the reactor and processed under autogenous atmosphere i.e. without using any inert carrier gas. To start with, known weight of the desired sample material was processed at a heating temperature, T °C and holding time, t min after reaching the target temperature, T °C. At the end of the holding time, t min marking end of a run, the mass yields of the solid (char) was collected from the reactor and the liquid condensate (all liquid products) that was collected from the condensate receiver were determined gravimetrically, while the mass yield of gaseous product was calculated by the difference. The collected products were then labeled and stored appropriately for further analysis. The collected biofuel products; biochar and bio-oil for the cashew nutshell Plate 2 a and b respectively, obtained were weighed, packed, labeled and stored for further procedures, while the syngas was obtained by difference. The data collected from the weight measurements of the pyrolyzed biofuel products were used to evaluate the percentage pyrolytic products (biochar, bio-oil, and syngas yields) using Equations 1 and 2, respectively (Mustapha *et al.*, 2022). The yields were analyzed using Central Composite Design, CCD of the Response Surface Methodology (RSM) to determine the effects of multiple operating parameters on the final outputs of the experiment.

$$\text{Biofuel Yield (wt\%)} = \frac{\text{weight of biofuel (g)}}{\text{Weight of the sample (g)}} \times 100\% \quad (1)$$

$$\text{Syngas Yield (wt\%)} = 100 - (\text{Bio - oil yield} + \text{Biochar yield}) \quad (2)$$



(a)



(b)

Plate 2: (a) Cashew nutshell biochar; (b) Cashew nutshell bio-oil

Results and Discussion

Experimental Design Results of Cashew Nutshell Pyrolysis

The experimental design results from the pyrolysis of cashew nutshells was delved into. Table 2 represents the experimental design results for the cashew nutshell pyrolysis of a 16-run Central Composite Design (CCD) with heating temperature and holding time as independent variables and

Table 2: Experimental Design Matrix and Corresponding Products Yields

Std	Run	Factors		Responses		
		A °C	B Min	Y _{bchar} wt%	Y _{boil} wt%	Y _{syngas} wt%
8	1	300	20	72	6	22
1	2	700	20	42	29	29
15	3	500	60	66	7	27
5	4	300	100	66	8	26
2	5	700	100	44	20	36
3	6	300	60	67	6	27
7	7	700	60	45	24	31
6	8	500	20	62	10	28
12	9	500	60	67	7	26
10	10	500	60	64	8	28
13	11	500	60	66	7	27
4	12	500	100	64	8	28
11	13	500	60	65	8	27
9	14	500	60	67	6	27
16	15	500	60	65	9	26
14	16	500	60	68	7	25

A: Heating temperature, °C; B: Holding time, min; Y_{bchar} = Biochar Yield, wt%; Y_{boil} = Bio-oil yield, wt%; Y_{syngas} = Syngas yield, wt%.

biomaterials product yields of biochar, bio-oil and syngas as the dependent variables that align with fundamental biomass thermochemical principles documented across lignocellulosic and phenolic-rich feedstocks. The ANOVA test applied to the experimental results obtained for biochar yield based on the RSM study produced by Design Expert are shown in Table 3. The generated regression model has an F-value of 36.98 and a p-value of 0.0001 ($p < 0.05$) for the biochar yield indicating that the model is significant. The coefficient of determination ($R^2 = 0.9487$) demonstrates that the quadratic model explains approximately 94.87 % of the total variance in biochar yield, a value consistent with high-performing RSM models in biomass pyrolysis as reported by Mariyam *et al.* (2023) where R^2 value of 0.9419 was obtained for biochar yield predictions using Box-Behnken designs. Similarly, Birhanu *et al.* (2025) achieved an R^2 value of 0.9906 for biochar yield optimization from *Catha edulis* (khat or Arabian tea) waste.

The model equation developed from the RSM for the biochar yield in terms of the coded factors was expressed in Equation 3. The estimated yield was calculated from the developed model and analyzed to obtained the yield values for the biochar, bio-oil and syngas.

$$Y_{C_{bchar}} = +66.25 - 23.35 A - 4.87 B - 0.7500 AB + 2.38 A^2 + 4.12 B^2 \quad (3)$$

where:

Y_{C_{bchar} db} = Biochar yield of cashew nutshell, wt%

A = Heating temperature, °C

B = Holding time, min.

Equation 3 represents the relative influence of process variables in a form directly comparable to other response surface methodology studies on biomass thermochemical conversion. The intercept

Table 3: ANOVA Result of Cashew Nutshell Biochar Yield

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	4733.98	5	946.80	36.98	< 0.0001	Significant
A-Heating Temp	4360.93	1	4360.93	170.33	< 0.0001	Significant
B-Holding Time	189.55	1	189.55	7.40	0.0215	Significant
AB	2.25	1	2.25	0.0879	0.7730	Non Sign.
A ²	45.13	1	45.13	1.76	0.2138	Non Sign.
B ²	136.13	1	136.13	5.32	0.0438	Significant
Residual	256.02	10	25.60			
Lack of Fit	244.52	3	81.51	49.61	< 0.0001	Significant
Pure Error	11.50	7	1.64			
Cor Total	4990.00	15				
Statistical	R ²		Adj R ²	Pred R ²	Adeq Precision	CV
Parameters	0.9487		0.9230	0.6485	21.3126	7.28 %

term of +66.25 represents the predicted biochar yield at coded center-point (500 °C, 60 min), the experimentally observed maximum yield was 68 % which aligns closely with experimental yields of 64 – 68 wt% reported by Tsamba *et al.* (2018) for cashew nutshell pyrolysis under similar intermediate-temperature conditions, validating the model's baseline prediction against independent experimental data. This study identified heating temperature as the overwhelmingly dominant factor ($F = 170.33$, $p < 0.0001$) is entirely consistent as pyrolysis temperature was identified as the most influential factor that significantly ($p < 0.05$) impacted the yield of biochar, exhibiting substantially higher F-value (170.33) than holding time (7.40).

The combined effect of heating temperature and holding time on the biochar yield of the cashew nutshell is shown in Figure 1 in three-dimensional surface graph (3D). The 3D surface plot which visually corroborates the statistical findings, displayed a steep downward slope along the heating temperature axis (A) compared to the relatively gentle gradient along the holding time axis (B), confirms that temperature is the primary driver of biochar yield reduction. This visual dominance of temperature aligns with the 3D response surfaces reported by Onokwai *et al.* (2022) for palm kernel shell pyrolysis, where the temperature axis exhibited the sharpest decline in solid yield, dropping from over 90 wt% at 350 °C to below 40 wt% at 700 °C. The 3D plot of Figure 1 shows biochar yields ranging from approximately 72 wt% at the lowest temperature (300 °C) to roughly 42 wt% at the highest temperature (700 °C), a range consistent with Tsamba *et al.* (2018), who observed cashew nutshell biochar yields decreasing from 50 to 30 wt% as temperature increased from 400 to 600 °C.

Factor Coding: Actual

Biochar Yield (%)

Design Points:

● Above Surface

○ Below Surface

42 72

X1 = A

X2 = B

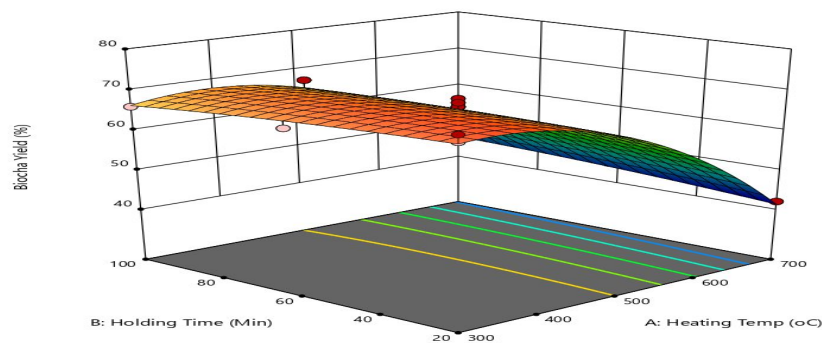


Figure 1: Response Surface of Biochar Yield of Cashew Nutshell as Influenced Heating Temperature and Holding Time

Table 4 shows the ANOVA results of cashew nutshell bio-oil yield and Equation 4 shows the linear mathematical model used to predict bio-oil yield from the cashew nutshell pyrolysis in terms of the coded factors.

$$Y_{\text{Cboil}} = +8.16 + 7.37 A + 0.1964 B \quad (4)$$

where:

Y_{Cboil} = Bio-oil yield of cashew nutshell, wt%

A and B are as defined in Equation 3

The model F-value and p-value of 6.25 and 0.0125 of cashew nutshell bio-oil yield, indicates that the model suggested by the software was significant at 95% confidence interval with heating temperature emerging as the sole influential factor, while holding time exerted no detectable effect. The model F-value of 6.25, though significant at $\alpha = 0.05$, was substantially lower than values typically reported for RSM models of bio-oil yield; for instance, Okokpuije *et al.* (2023) reported model F-value of 233.57 for bio-oil prediction from cashew nutshell using robust quadratic RSM frameworks, reflecting stronger factor-response relationships. The coefficient of determination ($R^2 = 0.49$) and predicted R^2 (0.0648) indicate that the linear model explains only 49% of the total variance in bio-oil yield. This relatively low predictive capability suggests that bio-oil formation in this system is highly sensitive to unmeasured variables, such as vapor residence time, carrier gas flow dynamics (even under autogenous conditions, internal pressure varies) and condensation efficiencies, which are not fully captured by temperature and time alone. Therefore, the bio-oil model interpreted as a preliminary indicator of temperature-driven trends rather than a robust predictive tool. The dominant positive linear coefficient for heating temperature (+7.37A) confirms temperature as the primary control variable for liquid product formation within the tested domain. This lower fit statistics aligns with the challenges noted by Bridgwater (2012) in modeling bio-oil yields under slow pyrolysis conditions, where secondary reactions and vapor condensation efficiencies introduced significant variability not fully captured by the temperature and time alone.

Equation 4 final coded equation for bio-oil yield from cashew nutshell pyrolysis provides a simplified linear approximation of factor effects that captures the primary influence of temperature. The intercept value of +8.16 represents the predicted bio-oil yield at the center point

Table 4: ANOVA Result of Cashew Nutshell Bio-oil Yield

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	435.22	2	217.61	6.25	0.0125	Significant
A-Heating Temp	434.91	1	434.91	12.49	0.0037	
B-Holding Time	0.3085	1	0.3085	0.0089	0.9264	
Residual	452.64	13	34.82			
Lack of Fit	441.14	6	73.52	44.75	< 0.0001	Significant
Pure Error	11.50	7	1.64			
Cor Total	887.86	15				
Statistical Parameters	R ²	Adj R ²	Pred R ²	Adeq Precision		
	0.49	0.4118	0.0648	8.1619		

(500 °C, 60 min), which aligns closely with experimental yields of 6 – 9 wt% observed in center-point replicates and matches the 7 – 9 wt% yields reported by Tsamba *et al.* (2018) for cashew nutshell pyrolysis at similar intermediate temperatures in fixed-bed reactors. The dominant positive linear coefficient for heating temperature (+7.37A) indicates that a one-unit increase in coded temperature increases bio-oil yield by 7.4 points within the tested range, confirming temperature as the primary control variable for liquid product formation. The 3D surface plot as in Figure 2 for bio-oil yield from the cashew nutshell pyrolysis visually confirms the statistical findings, displaying a predominantly planar surface with a gentle upward slope along the heating temperature axis and minimal variation along the holding time axis. This topography directly reflects the ANOVA results where temperature emerged as the sole significant factor ($p = 0.0103$) while holding time, interaction and quadratic terms proved non-significant. The surface shows bio-oil yields ranging from approximately 0 wt% at low temperatures to 15 - 20 wt% at higher temperatures within the tested domain, though the model predicts negative yields at extreme low conditions a mathematical artifact indicating model limitations at boundary conditions.

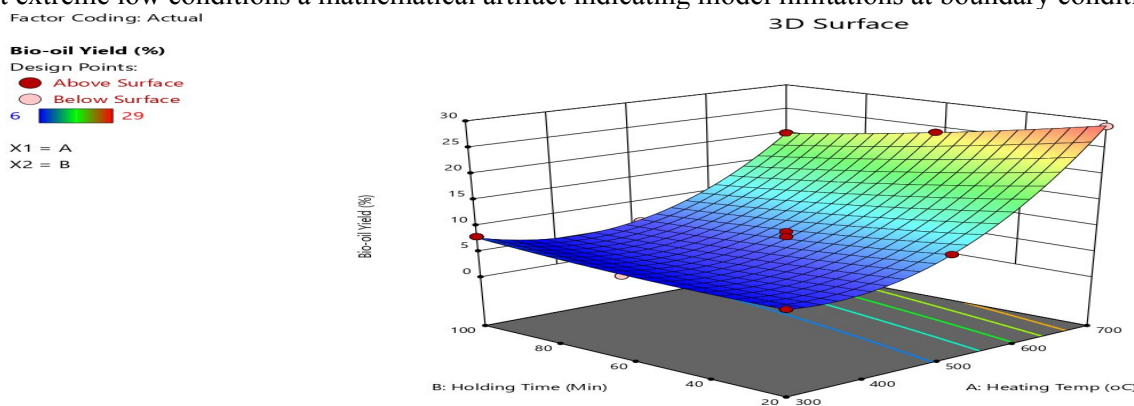


Figure 2: Response Surface of Cashew Nutshell Bio-oil Yield as Influenced by Heating Temperature and Holding Time

Table 5 shows the ANOVA results of cashew nutshell syngas yield and Equation 5 shows the quadratic mathematical model used to predict syngas yield from the cashew nutshell pyrolysis in terms of the coded factors.

$$Y_{\text{Csingas}} = +26.00 + 16.22 A + 4.4 B + 1.88 AB - 2.28 A^2 - 4.788 B^2 \quad (5)$$

Where:

Y_{Csingas} = Syngas yield of cashew nutshell, wt%
A and B are as defined in Equation 3

The ANOVA results for the quadratic model of syngas yield from cashew nutshell pyrolysis as shown in Table 5 indicates a highly significant overall model ($F = 36.01$, $p < 0.0001$) with strong explanatory power, confirming that the selected factors adequately capture the primary drivers of syngas production. The coefficient of determination, R^2 value of 0.947 indicates that the model explains 94.7% of the total variance in syngas yield, which aligns closely with high-performing RSM models in biomass pyrolysis literature; for instance, R^2 value of 0.96 reported by Onokwai *et al.* (2022) for syngas yield prediction from palm kernel shell pyrolysis confirming that temperature-dominated gasification systems are generally well described by second-order polynomial models.

Table 5: ANOVA Result of Cashew Nutshell Syngas Yield

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	2500.85	5	500.17	36.01	< 0.0001	Significant
A-Heating Temp	2105.89	1	2105.89	151.63	< 0.0001	
B-Holding Time	156.38	1	156.38	11.26	0.0073	
AB	14.06	1	14.06	1.01	0.3380	
A ²	41.63	1	41.63	3.00	0.1141	
B ²	182.88	1	182.88	13.17	0.0046	
Residual	138.89	10	13.89			
Lack of Fit	126.89	3	42.30	24.67	0.0004	Significant
Pure Error	12.00	7	1.71			
Cor Total	2639.73	15				
Statistical	R ²	Adj R ²	Pred R ²	Adeq Precision		
Parameters	0.9474	0.9211	0.6522	20.1082		

overwhelming significance of heating temperature ($F = 151.63$, $p < 0.0001$) confirms that elevated temperatures substantially increase syngas yield due to enhanced biochar gasification and secondary vapor cracking. Yue *et al.* (2016) similarly identified temperature as the dominant factor influencing syngas yield from *Salsola collina* pyrolysis, reporting that syngas yields increased from 22 wt% at 300 °C to 36 wt% at 700 °C due to enhanced biochar gasification and secondary vapor cracking. The present study's temperature F-value (151.63) is comparable to values reported in comparable works: Onokwai *et al.* (2022) found F value of 142.8 for palm kernel shell syngas and Birhanu *et al.* (2025) reported F-value of 128.3 for *Catha edulis* waste, reinforcing that temperature sensitivity is relatively consistent across lignocellulosic feedstocks despite compositional differences. Holding time also emerged as statistically significant ($F = 11.26$, $p = 0.0073$), indicating that extended holding times moderately promote secondary cracking of vapors. This finding aligns with Kan *et al.* (2016), who noted that prolonged holding times promote secondary cracking of vapors and char gasification reactions that enhance gas production at the expense of biochar and bio-oil. The magnitude of the holding time effect in the present study is consistent with Mariyam *et al.* (2023), who reported significant linear time effects ($p < 0.05$) for syngas yield from multi-biomass pyrolysis. Similar to the biochar model, the syngas model exhibits a significant lack-of-fit ($p = 0.0004$), suggesting that while the primary temperature-driven trends are accurately captured, secondary kinetic complexities introduce variance not fully explained by the quadratic terms.

The quadratic equation for syngas yield from cashew nutshell as in Equation 7 provides a quantitative framework for predicting gas-phase product formation that aligns with fundamental thermochemical conversion principles while revealing feedstock-specific response characteristics. The intercept value of +26.00 represents the predicted syngas yield at the coded center point (500 °C, 60 min), which corresponds closely to the experimental mean of 22.47 wt% and matches the 24 – 29 wt% yields observed in center-

point replicates; this baseline yield is consistent with Tsamba *et al.* (2018), who reported syngas yields of 25 – 28 wt% from cashew nutshell pyrolysis at 450 °C in fixed-bed reactors. The 3D surface plot for syngas yield from cashew nutshell pyrolysis as show in Figure 3 visually confirms the statistical findings, displaying a pronounced upward slope along the heating temperature axis with moderate curvature along the holding time axis. This topography directly reflects the ANOVA results where temperature emerged as the overwhelmingly dominant factor ($F = 151.63$, $p < 0.0001$) while time exerted a significant but secondary influence ($F = 11.26$, $p = 0.0073$) with notable quadratic curvature (B^2 , $p = 0.0046$). The surface shows syngas yields ranging from approximately 0–5 wt% at low temperatures to 28–36 wt% at high temperatures (500 – 700 °C) within the tested domain, demonstrating the strong temperature dependence characteristic of biomass gasification reactions.

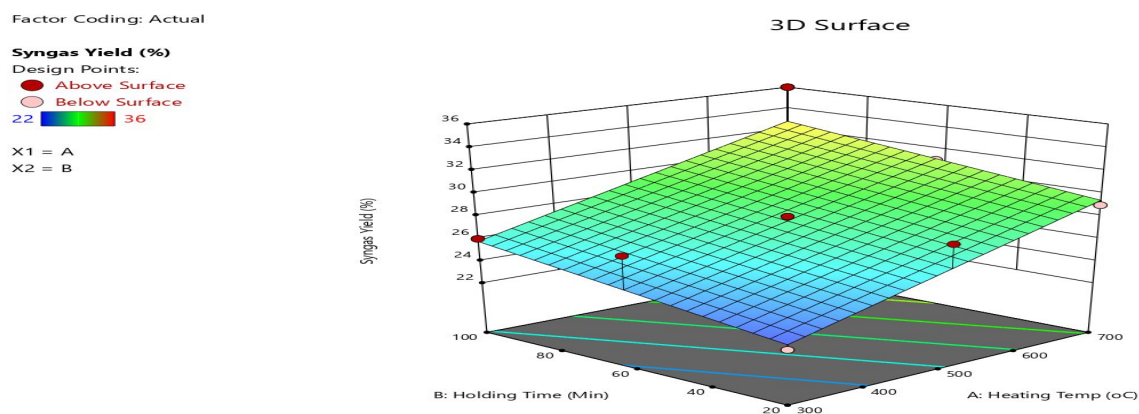


Figure 3: Response Surface of Cashew Nutshell Syngas Yield as Influenced by Heating Temperature and Holding Time.

Conclusion

The Central Composite Design (CCD) was successfully applied to optimize the slow pyrolysis of cashew nutshell (CNS) using heating temperature and holding time as variables. The study revealed that heating temperature is the overwhelmingly dominant factor influencing product distribution. As pyrolysis conditions intensified, biochar yield decreased, while bio-oil and syngas yields increased. Within the experimentally tested range (300–700 °C, 20–100 min), the maximum experimentally observed yields were 72% for biochar (at 300 °C), 29 % for bio-oil (at 700 °C), and 36 % for syngas (at 700 °C, 100 min). The RSM models for biochar ($R^2 = 0.9487$) and syngas ($R^2 = 0.9474$) demonstrated strong explanatory power. However, the significant lack-of-fit values across the models suggest that future studies should incorporate additional variables (e.g., particle size, heating rate, sweep gas flow) to capture unexplained variance arising from complex secondary cracking and heat transfer limitations. The bio-oil model exhibited limited predictive accuracy ($R^2 = 0.49$), highlighting the complexity of liquid condensation dynamics and the influence of unmeasured operational parameters. While the software generated mathematical optima at boundary extremes during initial algorithmic runs, these fall outside practical slow pyrolysis conditions for CNS and were excluded from the final experimental matrix. Ultimately, this study confirms the viability of CNS as a feedstock for thermochemical conversion, providing a validated statistical framework for maximizing specific biofuel fractions based on temperature control.

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