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# Effect Of Torrefaction On The Energy Characteristics Of Milled Corn Stover For Bioenergy Applications

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***ABSTRACT:*** *Agricultural residues represent an important renewable resource for sustainable bioenergy production, yet their direct utilization is often constrained by low energy density and unfavorable fuel properties. This study investigates the effect of torrefaction on the energy characteristics of milled corn stover (MCS) to improve its suitability for solid biofuel applications. Torrefaction was conducted within the temperature range of 200–300 °C under varying residence times and heating rates. The energy performance of raw and torrefied MCS was evaluated using Higher Heating Value (HHV), Lower Heating Value (LHV), and calorific value (CV) analyses. Results showed a progressive increase in HHV from 16.28 MJ/kg in raw MCS to 18.67 MJ/kg at 300 °C, while LHV increased from 16.05 MJ/kg to 17.87 MJ/kg. Statistical modeling revealed that reaction temperature was the most influential parameter affecting CV, with significant interaction effects among torrefaction variables. The optimized torrefaction conditions yielded densified MCS with enhanced energy density and reduced moisture content. These findings confirm that torrefaction is an effective pretreatment method for upgrading corn stover into a high-quality solid biofuel for bioenergy applications.*

**Keywords:** Torrefaction; Corn stover; Energy characteristics; Heating value; Bioenergy

## 1. Introduction

The increasing global demand for sustainable and low-carbon energy has intensified interest in renewable energy resources capable of supplementing or replacing fossil fuels (Bishoge *et al*., 2019). Among these resources, biomass occupies a strategic position due to its carbon neutrality, wide availability, and compatibility with existing thermochemical conversion technologies (Alcocer-García *et al*., 2025). Lignocellulosic agricultural residues are particularly attractive because they are generated as by-products of food production, thereby minimizing land-use competition and avoiding direct conflicts with food security (Toor *et al*,. 2020 ;Vieira *et al*., 2020). Their utilization for bioenergy not only contributes to energy diversification but also offers an environmentally sound pathway for waste management and rural economic development (Lacrosse *et al*., 2021; Rather *et al*., 2022).

According to Amotoe-Bondzie *et al*. 2026 Corn stover, which comprises stalks, leaves, husks, and cobs remaining after maize harvest, is one of the most abundant agricultural residues globally. In maize-producing regions, especially in developing economies, large quantities of corn stover are underutilized or disposed of through open-field burning, resulting in environmental pollution and greenhouse gas emissions (Zhou *et al*., 2025). From a resource perspective, corn stover represents a significant and renewable feedstock for solid biofuels and thermochemical energy systems, including combustion, gasification, and co-firing applications (Amotoe-Bondzie *et al*. 2026

Despite its abundance, the direct use of raw corn stover as a solid biofuel is constrained by several inherent physicochemical limitations. High inherent moisture content, low bulk density, and relatively low heating value reduce its energy efficiency and increase transportation and handling costs (Menor *et al*.,; 2026). In addition, poor grindability and heterogeneous particle size distribution negatively affect downstream processing and combustion performance. These drawbacks limit the competitiveness of untreated corn stover when compared with conventional fossil fuels such as coal (Zhou *et al*., 2025).

Torrefaction has emerged as an effective thermochemical pretreatment technique for upgrading lignocellulosic biomass. Conducted at moderate temperatures ranging from 200 to 300 °C under inert or oxygen-limited conditions, torrefaction induces partial devolatilization and structural transformation of biomass (Nair *et al*., 2025; Oginni *et al*., 2024; Cen *et al*., 2022). During the process, hemicellulose is preferentially decomposed, while cellulose and lignin remain relatively stable. This selective degradation leads to a reduction in moisture content, an increase in fixed carbon, and a decrease in oxygen-to-carbon ratio, thereby improving the fuel quality of the biomass (Chen *et al*., 2018).

Several studies have demonstrated that torrefaction enhances key energy characteristics of biomass, including higher heating value (HHV), lower heating value (LHV), and overall energy density. The process also improves hydrophobicity, storage stability, and grindability, making torrefied biomass more suitable for long-distance transport and industrial handling (Ivanovski *et al*., 2023). When torrefaction is combined with size reduction through milling, the resulting material exhibits more uniform particle

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characteristics and enhanced calorific performance, facilitating efficient energy conversion. In many cases, torrefied and milled biomass shows fuel properties comparable to low-rank coal, enabling its potential use in co-firing and other conventional energy systems with minimal modification (Chen *et al*., 2018; Bach *et al*., 2017).

Although the effects of torrefaction on various biomass feedstocks have been widely investigated, limited attention has been given to the specific influence of torrefaction on the energy characteristics of *milled* corn stover. Milling alters surface area, particle size distribution, and thermal behavior, which may interact with torrefaction severity to influence calorific outcomes. Understanding these interactions is essential for optimizing pretreatment conditions and maximizing energy recovery from corn stover (Chen *et al*., 2023; Mpungu *et al*., 2026).

Therefore, this study investigates the effect of torrefaction on the energy characteristics of milled corn stover, with particular emphasis on changes in heating values and calorific performance relevant to bioenergy applications. The findings aim to contribute to the development of efficient biomass upgrading strategies that enhance the viability of corn stover as a sustainable solid biofuel.

## 2. MATERIALS AND METHODS

The materials and equipment/methods used in this research are presented below.

### 2.1 Materials and Equipment

The primary feedstock, corn stover, was sourced from the research farm of the School of Agricultural Technology at the Federal University of Technology, Akure (FUTA) (7°17′–7°19′N, 5°7′–5°9′E). Nigeria. To maintain an inert environment and prevent thermo-oxidative degradation during torrefaction, high-purity nitrogen gas ($N_2$) was utilized. Key equipment comprised a fixed-bed stainless steel torrefaction reactor, a laboratory drying oven, a hammer mill, and a sieve shaker. Analytical instrumentation included a muffle furnace, an automated pelletizer for densification, K-type thermocouples for thermal monitoring, a precision electronic balance, a bomb calorimeter, and a moisture analyzer.

### 2.2 Methods

Samples were manually cleaned to eliminate debris and degraded fractions. The residue was mechanically shredded into 5–10 cm segments and sun-dried under ambient conditions (30–35 °C) for 5–7 days until the moisture content was reduced to <10% (Chen *et al*., 2021).

To inhibit microbial activity, the dried material was cooled to <5 °C before being processed in a hammer mill to a particle size of 1–2 mm. The resulting fraction was sieved to isolate particles between 0.5 and 1.0 mm and stored in airtight polyethylene bags with desiccants to ensure hygroscopic stability (Fuad *et al*., 2020).

### 2.2 Torrefaction Process

Thermal pretreatment was executed in a fixed-bed stainless steel reactor under continuous nitrogen flow. Samples were subjected to a range of torrefaction temperatures (T = 200, 220, 240, 260, 280, and 300 °C) across varying residence times (t = (30, 45, and 60 minutes), to evaluate the kinetics of the process (Medic *et al*., 2012). Heating rates were strictly controlled via K-type thermocouples. Upon completion of the designated residence time, the torrefied biomass was cooled to ambient temperature under nitrogen flow to prevent spontaneous combustion. Samples were subsequently stored in airtight containers for characterization (Okekunle *et al*., 2020; Fuad *et al*., 2020)

The torrefaction processes for the thermal treatment of both MCS and pelletized MCS were carried out using a locally fabricated fixed-bed, bench-scale reactor used to conduct laboratory scale torrefaction studies to understand the effect of product properties **(**Tumuluru *et al*., 2021). The reactor, with an average capacity of 80 liters, is designed to process up to 5 kg of biomass per batch. For each experiment, approximately 2 kg of biomass was loaded into the reactor tube. The reactor tube was sealed using an adjustable gasket to ensure an airtight environment, preventing air infiltration and vapor leakage. Bolts were tightened on the reactor lid to further secure the system. To monitor temperature accurately, three K-type thermocouples were strategically positioned within the reactor tube, spaced 200 mm apart. These thermocouples measured the incoming gas temperature, the temperature at the biomass bed, and the outgoing gas temperature. They were connected to an external temperature controller, allowing for easy monitoring and adjustment. To maintain an inert environment, nitrogen gas was introduced into the reactor at a controlled flow rate of $1.2 \times 10^{-3}$ m³/min, regulated by a valve and flow meter (Chen *et al*., 2023).

The reactor was gas-fired, using an external fuel source to heat the biomass. The process was carried out using the method described by Chen *et al*. (2018). The furnace temperature was raised from ambient to 150°C at a rate of 10°C/min. This initial phase was maintained for several minutes to remove residual moisture. The temperature was then increased to the target levels specific to each torrefaction run. Once the desired temperature was reached, the biomass was held at this temperature for a specified residence time, ensuring uniform thermal treatment. After the torrefaction process, the samples were rapidly cooled using nitrogen gas to prevent further thermal reactions (Mpungu *et al*., 2026 ). For MCS, multiple samples were torrefied across a temperature range of 200°C to 300°C, with increments of 20°C at 60 minutes each. The color of the MCS during this process was observed to change from light yellow to dark yellow and eventually to very dark brown colour. The torrefaction of pelletized MCS ash followed a Box-Behnken experimental design, allowing for systematic optimization of the process conditions (Fuad *et al*., 2020).

### 2.3 Densification Process

The densification of the raw MCS was performed using a pelletizing technique. The densification of torrefied corn stover was conducted using a pelletizer to improve its energy density, handling, and storage properties. The preconditioned stover was then fed into a pelletizer. The pelletizing machine was used to compress the material under an average pressure of 10 MPa at a preheating temperature of 150°C, while the starch was used as the binder. The densification was performed in controlled batches, producing uniform pellets that were cylindrical in shape and consistent in size and density with an average diameter and length of 6 mm and 15 mm respectively by standard procedure (Maj *et al*., 2022; Orisaleye *et al*., 2018)

### 2.4 Energy Content Analysis

The energy content (HHV) of the biomass samples was determined by measuring their calorific value (CV) or higher heating value on a dry basis using a bomb calorimeter, as described by (Daskin, 2024). The calorimeter system consisted of a ballistic calorimeter, oxygen supply, and a galvanometer. The biomass samples, after thorough grinding and drying, were introduced into the calorimeter crucible at a mass of 0.25 g. A cotton thread was placed between the fire tube and the center of the test specimen to initiate combustion. The bomb was securely positioned within the calorimeter, and oxygen was supplied at a pressure of 25 bar. The galvanometer was calibrated to zero, and the ambient temperature inside the bomb was monitored for 30 seconds. Upon ignition, the maximum temperature rise was recorded by the galvanometer. The CV was calculated using the following Equation 1: (Ismaila *et al*., 2024).

$$\mathrm{CV} = \frac{\mathrm{Q_1 - Q_0}}{\mathrm{m}} \times \mathrm{C} \qquad (1)$$

Where CV is the CV (HHV) in MJ/kg, $Q_1$ is the Galvanometer reading with the sample in degree celsius. $Q_0$ is the Galvanometer reading without sample degree celsius, C is the constant for calibration, and m is the mass of sample (g).
This method was applied for both the calibration samples of benzoic acid and the test samples, following the procedures outlined by (Daskin (2024); Kwaghger *et al*., 2017).

### 2.5 Statistical Analysis

Response Surface Methodology (RSM) was employed to analyze the effects of reaction temperature, residence time, and heating rate on CV. Analysis of variance (ANOVA) was used to determine the statistical significance of model terms, interactions, and quadratic effects.

## 3. RESULTS AND DISCUSSION

### 3.1 Effect of Torrefaction on Energy Content

The result of the energy content is presented in Table 1. The HHV increased from 16.28 MJ/kg in the raw sample to 18.67 MJ/kg at 300°C. Similarly, the LHV showed an increase from 16.05 MJ/kg in the raw sample to 17.87 MJ/kg at 300°C.
Figure 1 presents the result of energy content analysis of the corn stover samples. The higher heating value (HHV) of the milled corn stover (MCS) samples progressively increases from 16.28 MJ/kg in the raw sample to 18.67 MJ/kg in MCS300, reflecting the total energy content, including the latent heat of vaporization of water. Conversely, the LHV, which excludes the energy associated with water vaporization, increases from 16.05 MJ/kg to 17.87 MJ/kg over the same torrefaction range.

Table 1: Energy Analysis of the Raw MCS and Torrefied MCS

| Properties (%) | Raw Sample | Torrefied Samples of MCS (200 – 300ºC) | | | | | |
|---|---|---|---|---|---|---|---|
| | RCS | 200 | 220 | 240 | 260 | 280 | 300 |
| HHV | 16.28±0.4 | 16.34±0.4 | 16.75±0.5 | 17.34±0.3 | 17.88±0.4 | 18.55±0.5 | 18.67±0.4 |
| LHV | 16.05±0.5 | 16.15±0.5 | 16.22±0.7 | 16.91±0.3 | 17.25±0.4 | 17.59±0.4 | 17.87±0.4 |

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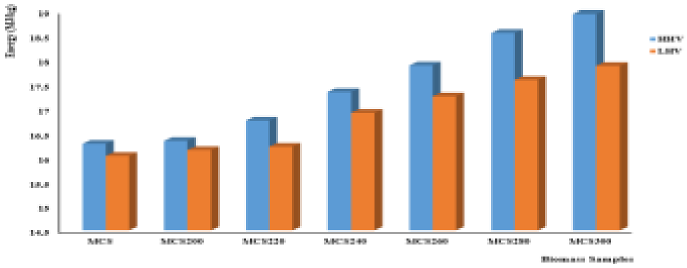

**Figure 1: Energy Analysis of the Corn Stover (MCS) Samples**

From Figure 1, the consistent gap between the higher heating value (HHV) and lower heating value (LHV) highlights the significant influence of moisture and hydrogen content, both of which decrease substantially during the torrefaction process. These reductions enhance the LHV, rendering the torrefied biomass more energy-efficient for practical applications by minimizing the energy lost to moisture evaporation during combustion.

The observed enhancements are primarily attributed to the thermal decomposition of oxygenated compounds and light volatiles during torrefaction, which concentrates the energy-dense carbon content within the biomass structure. The increase in HHV is directly correlated to the decline in oxygen-to-carbon and hydrogen-to-carbon ratios, resulting in a material with superior combustion efficiency and a greater net energy yield, a finding supported by the research of Tumuluru (2015) and Chen *et al*. (2018) The LHV follows a similar upward trend, as the reduction in moisture content minimizes the latent heat losses typically associated with water evaporation in combustion systems. Consequently, these improvements in energy content render torrefied corn stover increasingly comparable to coal in terms of calorific value, positioning it as a robust renewable alternative for both large-scale thermal power generation and industrial heating applications (Daskin *et al*., 2024; Oginni *et al*., 2024; Cortazar *et al*., 2023; Tumuluru *et al*., 2021).

### 3.2 Effect of Torrefaction Conditions on Calorific Value

Table 2 presents the ANOVA and Fitness Analysis for the calorific value (CV). The overall model is highly significant, with an F-value of 113.05 and a p-value of less than 0.0001. The $R^2$ value of 0.9912 suggests that 99.12% of the variability in calorific value can be explained by the model, while the adjusted $R^2$ of 0.9825 indicates a strong fit even when accounting for the number of predictors. With an F-value of 50.52 and a p-value of 0.0001, reaction temperature is identified as a highly significant factor affecting CV. This factor also shows significance with an F-value of 6.70 and a p-value of 0.0322, indicating its role in enhancing energy content. Similarly, heating rate is significant (F-value = 30.34; p-value = 0.0006), further supporting its influence on calorific value. The analysis reveals significant interaction effects among factors (AB, AC, and BC), all with p-values below 0.001, highlighting that combinations of these parameters can synergistically impact CV. The lack of fit is not significant (p-value = 0.0876), suggesting that the model adequately captures the relationship between input variables and CV without substantial unexplained variation. Table 3 presents the final calorific value (CV) prediction equation in terms of actual and coded factors. The final calorific value (CV) prediction equation, derived from the analysis of actual and coded factors, provides a comprehensive framework for understanding the influences of reaction temperature, residence time, and heating rate on the energy content of densified and pelletized milled corn stover (MCS). The equation starts with a constant term of +51.27881, which serves as the baseline for the predicted calorific value. This indicates strong foundational energy content inherent in the biomass before considering the effects of the variables. The negative coefficient of -0.097078 for coded factor A indicates that increasing reaction temperature has a diminishing effect on CV when considered alone, while its positive contribution (+11.71) in actual terms suggests that higher temperatures generally enhance energy content. The coded factor B shows a significant negative coefficient (-0.836467), indicating that longer residence times can lead to decreased CV, which is counterintuitive but may reflect degradation effects at extended durations. The actual term (-11.63) reinforces this observation. Similar to residence time, the coded factor C has a negative coefficient (-0.066937), suggesting that higher heating rates may not be beneficial for maximizing CV. The actual term (-45.55) further emphasizes this trend. The positive interaction term for AB (+0.006768) and AC (+0.076626) indicates that the combination of reaction temperature with residence time and heating rate positively influences CV, suggesting synergistic effects that enhance energy content when these factors are optimized together. Conversely, the negative interaction term for BC (-0.183605) suggests that high values of both residence time and heating rate may detrimentally affect CV. The presence of negative quadratic coefficients for $A^2$ (-0.001199) and $C^2$ (-1.05489) implies that there are diminishing returns associated with increasing these factors beyond certain thresholds, indicating optimal ranges for maximizing CV.

**Table 2:** ANOVA and Fitness Analysis for the Calorific Value (CV)

| Source | SS | df | MS | F-value | p-value | Condition | $R^2$ | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|---|
| **Main Model** | 3.75 | 8 | 0.4693 | 113.05 | < 0.0001 | significant | 0.9912 | 0.9825 |
| A-Reaction Temperature | 0.2097 | 1 | 0.2097 | 50.52 | 0.0001 | | | |
| B-Residence time | 0.0278 | 1 | 0.0278 | 6.70 | 0.0322 | | | |
| C-Heating Rate | 0.1259 | 1 | 0.1259 | 30.34 | 0.0006 | | | |
| AB | 0.1179 | 1 | 0.1179 | 28.40 | 0.0007 | | | |
| AC | 0.1103 | 1 | 0.1103 | 26.58 | 0.0009 | | | |
| BC | 0.1313 | 1 | 0.1313 | 31.64 | 0.0005 | | | |
| $A^2$ | 0.1108 | 1 | 0.1108 | 26.70 | 0.0009 | | | |
| $C^2$ | 0.0997 | 1 | 0.0997 | 24.01 | 0.0012 | | | |
| **Residual** | 0.0332 | 8 | 0.0042 | | | | | |
| Lack of Fit | 0.0322 | 6 | 0.0054 | 10.74 | 0.0876 | not significant | | |
| Pure Error | 0.0010 | 2 | 0.0005 | | | | | |
| **Cor Total** | 3.79 | 16 | | | | | | |

**Table 3:** Final CV Prediction Equation in Terms of Actual and Coded Factor

| Actual Factors | | | Coded Factors | | |
|---|---|---|---|---|---|
| **$CV_{af}$ =** | +51.27881 | | **$CV_{cf}$ =** | +3.51 | |
| | -0.097078 | A | | +11.71 | A |
| | -0.836467 | B | | -11.63 | B |
| | -0.066937 | C | | -45.55 | C |
| | +0.006768 | AB | | +4.06 | AB |
| | +0.076626 | AC | | +17.62 | AC |
| | -0.183605 | BC | | -15.84 | BC |
| | -0.001199 | $A^2$ | | | |
| | -1.05489 | $C^2$ | | | |

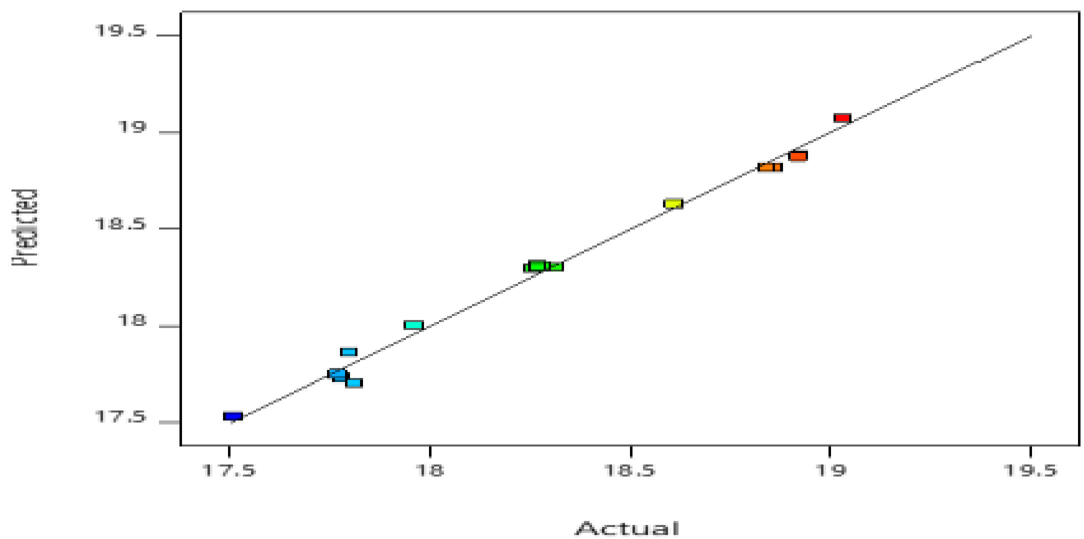


**Figure 2: The Graph of Predicted CV vs Actual CV**

From Table 2, it was observed that the quadratic model for CV is highly significant, as indicated by an F-value of 113.05 and a p-value of < 0.0001 as shown in Table 3. Also, The $R^2$ value of 0.9912 demonstrates that the model explains 99.12% of the variation in CV, with an adjusted $R^2$ of 0.9825, confirming the model's reliability (Daskin *et al*., 2024). Significant factors include reaction temperature (A), residence time (B), heating rate (C), and their interactions (AB, AC, BC), as well as quadratic terms ($A^2$, $C^2$) owing to their individual P-value (P-values ≤ 0.05) at 95% confidence interval. The non-significant lack of fit from the model also indicates that the model predictions align well with the observed data, making it reliable for practical applications (Zhou *et al*., 2025; Okenkule, *et al*., 2020).

The model equations in terms of actual and coded factors ($CV_{af}$ and $CV_{cf}$ ) are presented in Table 3 and Equations 1 respectively. The model reveals that CV increases with temperature, but excessive values beyond optimal ranges reduce CV due to excessive mass loss and energy content degradation according to Tumuluru, (2015).

$$CV_{af} = 51.27881 - 0.097078A - 0.836467B - 0.066937C + 0.006768AB + 0.076626AC - 0.183605BC - 0.001199A^2 - 1.05489C^2 \quad (10)$$

$$CV_{cf} = 3.51 + 11.71A - 11.63B - 45.55C + 4.06AB + 17.62AC - 15.84BC \quad (2)$$

The equation in terms actual factors can be used to make predictions of CV in terms of the actual values or levels of each factor, with each specified of its original unit, while the coded factors can be used to make predictions about the CV for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients, ensuring robust optimization of torrefaction conditions (Mpungu *et al*., 2026).

It was also observed from the analysis that the predicted versus actual CV graph shows a strong correlation, with points clustering closely around the line of equality, confirming the model's predictive reliability as shown in Figure 2. This analysis shows that Torrefaction enhances CV in densified MCS by increasing carbon content and reducing moisture and volatiles, as seen in the experimental data (Mpungu *et al*., 2026; Daskin *et al*., 2024).

### 3.3 Implications for Bioenergy Applications

The observed improvements in HHV, LHV, and CV confirm that torrefaction significantly upgrades the energy characteristics of milled corn stover. Reduced moisture content and increased energy density enhance combustion efficiency, storage stability, and handling performance. These improvements make torrefied MCS a promising feedstock for combustion, co-firing, and gasification systems, supporting its role in sustainable bioenergy production.

## 4. Conclusions

This study demonstrates that torrefaction significantly improves the energy characteristics of milled corn stover, as evidenced by consistent increases in higher heating value (HHV), lower heating value (LHV), and overall calorific value. The enhancement in fuel quality is primarily attributed to moisture reduction, devolatilization of oxygen-rich compounds, and the consequent enrichment of carbon content. Reaction temperature was identified as the most influential torrefaction parameter affecting energy performance, while significant interaction effects among temperature, residence time, and heating rate highlight the importance of process optimization. The results confirm that, under optimized conditions, torrefaction effectively upgrades corn stover into a high-quality solid biofuel with properties comparable to low-rank coal, making it suitable for a wide range of bioenergy applications, including combustion and co-firing systems.

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