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Effect of Torrefaction on Chemo-Physical Characteristics of Densified Corn Stover for Bioenergy Applications

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Abstract: *The escalating demand for renewable energy has spotlighted lignocellulosic biomass, particularly abundant agricultural residues like corn stover, as a viable alternative to fossil fuels. However, raw corn stover suffers from low energy density, high moisture susceptibility, poor handling properties, and inefficient combustion, limiting its direct use in bioenergy systems. This study investigates the integrated effects of torrefaction and densification on the chemo-physical properties of milled corn stover (MCS) sourced from Nigeria, aiming to upgrade it into a high-quality solid biofuel. Corn stover was torrefied in a fixed-bed reactor under nitrogen atmosphere at temperatures of 200–300 °C for 60 min residence time, followed by pelletization. Comprehensive characterization included ultimate analysis (C, H, O, N, S), molecular composition (hemicellulose, cellulose, lignin), proximate analysis (moisture, volatiles, fixed carbon, ash), and energy assessment (higher and lower heating values). Results showed progressive carbon enrichment (45.92% to 54.14%), reductions in oxygen (46.13% to 42.32%) and hydrogen (6.18% to 5.04%), and lowered O/C and H/C ratios, indicating coal-like characteristics. Hemicellulose degraded markedly (31.00% to 7.30%), volatiles decreased (76.5% to 40.1%), fixed carbon increased (17.7% to 36.9%), and higher heating value rose from 16.28 MJ/kg to 18.67 MJ/kg. Densification of torrefied material produced uniform pellets with enhanced calorific values (up to 19.03 MJ/kg), low moisture (down to 1.42%), and improved physical stability. These upgrades enhance hydrophobicity, storage durability, grindability, and combustion efficiency, making torrefied-densified corn stover suitable for co-firing, gasification, or standalone bioenergy applications. The process valorizes underutilized residues, mitigates open burning pollution, and supports sustainable energy in agricultural regions like Nigeria. Optimal torrefaction at 260–300 °C maximizes benefits, with future work recommended on scale-up, emissions, and techno-economic viability.*

Keywords: Torrefaction; Densification; Corn Stover; Biofuel Upgrading; Lignocellulosic biomass

1. INTRODUCTION

The growing demand for renewable and sustainable energy has intensified research into biomass as a viable alternative to fossil fuels, particularly in the context of climate change mitigation, energy security, and circular resource utilization (Tumuluru, 2015). Among available biomass resources, agricultural residues are especially attractive due to their abundance, low cost, and non-competition with food production. Corn stover has emerged as a promising feedstock for bioenergy systems owing to its wide availability and significant energy potential (Ochoa-Castaño et al., 2025; Shah et al., 2025).

Corn stover-comprising stalks, leaves, husks, and cobs remaining after maize harvest-is one of the most abundant agricultural residues globally and within Nigeria, where maize cultivation is concentrated in states such as Kaduna, Katsina, Borno, and Niger (Abdulmumini et al., 2023; Vikram, 2022). Despite its abundance, a substantial proportion of corn stover is either underutilized or disposed of through open-field burning, resulting in environmental pollution, greenhouse gas emissions, and significant loss of recoverable energy (Jekayinfa et al., 2020). Harnessing this residue for bioenergy therefore presents both an environmental and socio-economic opportunity.

However, the direct utilization of raw corn stover for energy applications is constrained by several inherent drawbacks. These include low bulk and energy density, high moisture affinity, poor grindability, and unfavorable handling, transportation, and storage characteristics. Collectively, these limitations reduce combustion efficiency and increase logistical and operational costs, thereby hindering large-scale deployment (Jena and Wallace, 2023; Hemmelgarn et al., 2023).

Torrefaction has been widely recognized as an effective thermochemical pre-treatment for upgrading lignocellulosic biomass. Conducted at temperatures between 200 and 300 °C in an inert or oxygen-limited environment, torrefaction selectively decomposes hemicellulose, reduces moisture and volatile content, and increases fixed carbon concentration and energy density (Medic et al., 2012; Chen et al., 2021). These changes enhance hydrophobicity, grindability, microbial resistance, and combustion behavior, making torrefied biomass more suitable for co-firing and other bioenergy conversion pathways (Orisaleye et al., 2022; Tumuluru et al., 2021; Majamo and Amibo, 2024).

In parallel, densification through pelletization or briquetting addresses the physical limitations of loose biomass by significantly increasing bulk density, mechanical strength, and geometric uniformity. This improves handling efficiency, reduces transportation and storage costs, and enables more stable and consistent combustion performance (Ibitoye et al., 2021; Marreiro et al., 2021; Nayomi et al., 2023).

The integration of torrefaction and densification offers synergistic benefits for bioenergy applications. While torrefaction enhances the chemical composition, energy density, and stability of biomass, densification improves its physical integrity and logistical performance. This combined approach is particularly relevant in Nigeria, where heavy reliance on traditional fuels has accelerated deforestation and exacerbated energy insecurity. Upgrading corn stover into high-quality solid biofuels provides a sustainable pathway for waste valorization with minimal competition for alternative uses (Adeleke et al., 2020; Reza et al., 2023).

Despite notable advances, comprehensive evaluations of how torrefaction parameters-particularly temperature and residence time-affect the chemo-physical, structural, and energetic properties of densified corn stover remain limited. Many existing studies focus on either torrefaction or densification in isolation, leaving gaps in understanding their combined effects on fuel quality. This study addresses this gap by systematically investigating the physicochemical, structural and energy characteristics of corn stover before and after torrefaction and densification, with the aim of assessing its suitability for advanced bioenergy applications.

2. MATERIALS AND METHODS

2.1 Materials and Equipment

Corn stover was used as the primary lignocellulosic feedstock and sourced from a research farm at the School of Agricultural Technology, Federal University of Technology, Akure, Nigeria. High-purity nitrogen gas (99.99%) was employed to maintain an inert atmosphere during torrefaction.

Major equipment included a fixed-bed stainless steel torrefaction reactor, drying oven, hammer mill, sieve shaker, muffle furnace, automated pelletizer, K-type thermocouples, precision electronic balance (±0.001 g), bomb calorimeter, moisture analyzer, and standard laboratory glassware.

2.2 Corn Stover Preparation

Corn stover was collected immediately after maize harvest between July and September 2024 in Akure, Nigeria (latitudes 7°17′–7°19′ N and longitudes 5°07′–5°09′ E) to minimize environmental contamination and biochemical degradation. The samples were manually sorted to remove soil, stones, and visibly degraded materials.

The cleaned stover was chopped into 5–10 cm lengths using a mechanical shredder and sun-dried under ambient conditions (30–35 °C) for 5–7 days until the moisture content fell below 10% (Chen et al., 2021). Dried samples were cooled at temperatures below 5 °C to suppress microbial activity prior to size reduction (Medic et al., 2012).

Approximately 25 kg of dried material was milled using a hammer mill and sieved to obtain particle sizes in the 0.5–1.0 mm range. The prepared samples were stored in airtight polyethylene bags containing desiccants until further processing (Medic et al., 2012; Tumuluru et al., 2021).

2.3 Torrefaction Procedure

Torrefaction was conducted in a fixed-bed stainless steel reactor under a continuous nitrogen flow to prevent oxidative reactions. Equal masses of prepared corn stover were subjected to torrefaction at temperatures of 200, 220, 240, 260, 280, and 300 °C, with residence times of 30, 45, and 60 minutes, to evaluate the influence of process severity (Medic et al., 2012; Tumuluru et al., 2021). The reactor temperature was regulated using K-type thermocouples and a programmable controller, with a controlled heating rate. Upon completion of torrefaction, samples were cooled to ambient temperature under nitrogen flow and stored in airtight containers prior to densification and analysis (Orisaleye et al., 2022).

2.4 Densification Procedure

Raw and torrefied corn stover samples were densified into pellets using an automated laboratory pelletizer to enhance bulk density and mechanical integrity. Approximately equal masses of material were fed into the pelletizer under controlled compression conditions. No external binders were added, relying on the thermoplastic behavior of lignin for particle bonding. Pellets were produced at a consistent die temperature and pressure, air-cooled to ambient conditions, and stored in sealed containers prior to physicochemical characterization (Ibitoye et al., 2021; Marreiro et al., 2021). This approach enabled direct comparison between raw densified and torrefied-densified corn stover.

2.5 Determination of Chemical Characteristics

Ultimate Analysis

Carbon (C) and hydrogen (H) contents were determined according to ASTM E777 using the combustion method. Approximately 2 g of powdered sample was combusted, and the resulting CO_2 and H_2O were absorbed in potassium hydroxide (KOH) and calcium chloride ($CaCl_2$) tubes, respectively. Carbon and hydrogen contents were as described by (Odogwu and Aseminaso, 2023; Medic et al., 2012) in equations 1 and 2.

$$\% \mathrm{C} = \left(\frac{12\mathrm{z}}{44\mathrm{x}}\right) \times 100 \quad (1)$$

$$\% \mathrm{H} = \left(\frac{2\mathrm{y}}{18\mathrm{x}}\right) \times 100 \quad (2)$$

where *x* is the sample mass (g), *y* is the mass increase of the $CaCl_2$ tube (g), and *z* is the mass increase of the KOH tube (g) (Medic *et al*., 2012; Soji-dekunle *et al*., 2025).
Nitrogen (N) content was determined following ASTM E778 (2021) using the Kjeldahl method. Approximately, 2.0 g sample digested in concentrated H_2SO_4 with K_2SO_4 and $CuSO_4$ catalysts; ammonia distilled into standard H_2SO_4 and back-titrated with NaOH.
The nitrogen content was calculated using Equation 3 as described by (Medic et al., 2012).

$$\% \mathrm{N} = \left(\frac{\text{Volume of acid used} \times \text{Normality}}{\text{Weight of con stover sample}}\right) \times 1.4 \quad (3)$$

while sulfur (S) was analyzed according to ASTM E775 2021 via bomb calorimetry and gravimetric determination of $BaSO_4$. 1 g combusted in bomb calorimeter under oxygen; ash extracted with dilute HCl, precipitated as $BaSO_4$ with $BaCl_2$, filtered, dried, and weighed. The sulfur content was calculated using Equation 4 as prescribed by (Medic et al., 2012; Mortensen et al., 2021).

$$\% S \ \left(\frac{0.1374\ y}{x}\right) 100 \quad (4)$$

Where x represents the weight of the original sample, and y denotes the weight of the $BaSO_4$ precipitate.
The oxygen content was determined using the method established by Akinola and Fapetu (2015). Biomass samples were ground to a fine powder (<1 mm particle size) and oven-dried to remove moisture. The prepared sample was analyzed using a CHNS analyzer, which quantified, and contents in mass percentages. The oxygen content was computed as described by Soji-dekunle *et al.*, 2025) in Equation 5.

$$O(\%) = 100 - (C + H + N + S + Ash) \quad (5)$$

Molecular (Structural) Analysis
Structural carbohydrate composition was determined using detergent fiber analysis. Hemicellulose content was calculated as the difference between neutral detergent fiber (NDF) and acid detergent fiber (ADF) (Ki *et al*., 2022). Cellulose was obtained from ADF through hydrolysis with 72% H_2SO_4 (Stefanidis et al., 2014)., while lignin content was measured as the acid-insoluble residue corrected for ash content (Ki et al., 2022; Medic et al., 2012; Tumuluru et al., 2021). All analyses were conducted in duplicate on a dry-weight basis.

Proximate Analysis
The moisture content (MC) analysis followed ASTM D1102 (1990) standards. A 0.1 kg portion of each sample was accurately weighed and placed into a pre-weighed dish. The dish was then transferred into a digital oven set to 110°C, where the sample was dried for approximately 30 minutes. The MC was calculated using the average of these measurements, following the method described by Oji *et al*. 2020 as in Equation 6:

$$\%\mathrm{MC} = \frac{\text{Weight in wet form} - \text{Weight when dry}}{\text{Weight in wet form}} \times 100 \quad (6)$$

The volatile matter content was determined according to ASTM E872-82 (1998) standards. Three samples were weighed and placed in a furnace preheated to 950°C. The samples were heated for 7 minutes, after which the volatile components were driven off, leaving behind ash and fixed carbon. Volatile matter was calculated by subtracting the weight of the ash from the dry weight of the sample, as expressed in Equation 7 (Onyeagba et al., 2016).

$$\%\ \mathrm{VM} = \frac{\text{Dry Sample Weight} - \text{Weight of the Ash}}{\text{Dry Sample Weight}} \times 100\% \quad (7)$$

Where VM = Volatile matter
The fixed carbon content (dry basis) was derived indirectly by subtracting the sum of the MC, ash content, and volatile matter content from 100%, The MC was calculated using following the method described by Oji et al. (2020) using the formula in Equation 8.

%FC = 100 – (%MC + %ASH + %VM) (8)

Where *FC* = Fixed carbon content (wt %), *MC* = Moisture content (wt %), *ASH* = Ash content (wt %), and *VM* = Volatile matter content (wt %).

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2.6 Determination of Physical Characteristics

Bulk density

The bulk density of the milled corn stover (MCS) was determined by following ASTM D6683-19 standard using a graduated cylinder with a known volume of 2000 cm³. The bulk density was calculated as described by Mohammad (2018) using the formula as shown in Equation 9:

$$\rho_{\mathrm{mcs}} = \frac{m_T - m_C}{m_2 - m_1} \quad (9)$$

Where , m_T, $and\ m_c$ represent the net mass of the material, the total mass of the cylinder filled with milled corn stover (MCS), and the mass of the empty cylinder, respectively, all measured in kilograms (kg). The sample volume V was determined in cubic centimeters (cm³). To ensure the reliability and reproducibility of the measurements, all determinations were performed in triplicate. The average values were subsequently calculated and expressed in kg/cm³.

2.7 Data Analysis

All experiments were conducted in duplicate, and average values with standard deviations were reported. Comparative analysis between raw and torrefied samples was performed to quantify the effects of temperature and residence time on the chemical and physical properties of corn stover.

3. RESULTS

3.1 Chemical Properties

Ultimate Composition

Table 1 presents the ultimate analysis of raw and torrefied MCS. Torrefaction significantly altered the elemental composition of the biomass.

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

Elements (%)	Raw Sample	Torrefied Samples of Milled Corn Stover (MCS) (200 – 300ºC)					
	MCS	200	220	240	260	280	300
C	45.92±0.5	45.96±0.3	46.32±0.5	47.15±0.4	47.94±0.5	50.07±0.5	54.14±0.6
H	6.18±0.05	5.96±0.05	5.61±0.02	5.57±0.05	5.5±0.05	5.42±0.06	5.04±0.05
O	46.13±0.2	45.92±0.5	45.28±0.1	44.62±0.3	43.91±0.5	43.84±0.5	42.32±0.6
N	0.48±0.2	0.48±0.4	0.49±0.2	0.53±0.5	0.61±0.2	0.69±0.2	0.73±0.2
S	0.11±0.03	0.18±0.01	0.18±0.07	0.32±0.03	0.34±0.03	0.36±0.05	0.41±0.03

All values are expressed on dry basis as a mean of two measurements ± standard deviation
Note that the residence time for each torrefaction process is 60 minutes

It can be observed from Table 1 that Carbon (C) content increased from 45.92% in raw MCS to 54.14% at 300°C, indicating enhanced energy density. The carbon enrichment is consistent with prior studies on torrefaction of lignocellulosic biomass, where increased torrefaction temperature promotes carbonization and reduction of oxygen content, improving fuel quality (Majomo and Amibo, 2024; Chen et al., 2023). Hydrogen (H) decreased from 6.18% to 5.04% in MCS 300, reflecting reduced volatile content These changes improve combustion properties and align with findings that thermal treatments increase the carbon-to-hydrogen ratio, enhancing energy density and reducing volatile emissions during combustion (Lomeda-De Mesa et al., 2020). Oxygen (O) decreased from 46.13% to 42.32%, improving combustion efficiency which aligns with studies on biomass torrefaction, highlighting oxygen removal as a critical factor in upgrading biomass to higher-quality solid fuels (Suxing et al., 2024; Ren et al., 2017). Nitrogen (N) and sulfur (S) showed slight increases, indicating minor changes during thermal treatment (Ren *et al*., 2017). Overall, torrefaction improved the fuel quality of corn stover by increasing carbon content and decreasing oxygen content, optimizing it for energy applications. The reduction in hydrogen and oxygen also contributes to a higher H/C and lower O/C ratio, which correlates with increased thermal stability and improved combustion characteristics, making the torrefied MCS more suitable for co-firing or standalone bioenergy applications. Torrefied corn stover can serve as a higher-grade solid biofuel with lower volatility, enhanced calorific value, and better handling and storage properties.

Proximate Composition

Table 2 presents proximate analysis results for raw and torrefied MCS.

Table 2: Proximate Analysis of the Raw Milled Corn Stover (MCS) and Torrefied

Properties (%)	Raw Sample	Torrefied Samples of MCS (200 – 300ºC)					
	MCS	200	220	240	260	280	300
VM	76.5±0.2	65.4±0.2	60.9±0.2	55.4±0.2	50.1±0.2	45.2±0.2	40.1±0.2
MC	12.3±0.3	10.5±0.2	9.2±0.3	8.1±0.3	7.3±0.2	4.5±0.3	2.3±0.3
FC	17.7±0.01	20.2±0.01	23.5±0.03	27.0±0.01	30.5±0.01	33.9±0.02	36.9±0.01
Ash	5.5±0.3	4.3±0.3	4.7±0.3	5.0±0.3	5.4±0.3	5.4±0.3	5.6±0.3

It can be observed from Table 2 that volatile matter (VM) decreased from 76.5% to 40.1%, moisture content (MC) from 12.3% to 2.3%, and fixed carbon (FC) increased from 17.7% to 36.9% with increasing torrefaction temperature. Ash content remained relatively stable (4.3–5.6%). These changes indicate improved energy density, stability, and combustion efficiency of torrefied MCS. These findings corroborate previous studies indicating that torrefaction densifies biomass energy by removing moisture and volatiles while increasing fixed carbon content (Ayúe and Serdar, 2017; Inegbedion, 2022; Özyuğuran and Yaman, 2017; Chen et al., 2021). Overall, torrefied MCS demonstrates improved fuel handling, storage stability, and higher heating value, making it suitable for industrial-scale bioenergy production.

Lignocellulosic Composition

Table 3 presents Molecular analysis of the the raw milled corn stover (MCS). Hemicellulose, cellulose, and lignin content decreased significantly with increasing torrefaction temperatures.

Table 3: Molecular Analysis of the Raw MCS and Torrefied MCS

Properties (%)	Raw Sample	Torrefied Samples of MCS (200 – 300ºC)					
	MCS	200	220	240	260	280	300
Hemicellulose	31.00±0.3	28.60±0.5	24.89±0.5	20.60±0.1	15.40±0.3	11.05±0.3	7.30±0.2
Cellulose	41.15±0.5	40.30±0.3	38.80±0.4	35.62±0.3	27.80±0.6	23.04±0.4	18.70±0.5
Lignin	6.15±0.4	5.61±0.3	4.82±0.3	3.90±0.3	2.74±0.4	2.23±0.3	1.43±0.3

From Table 3, Hemicellulose dropped from 31.00% to 7.30%, cellulose from 41.15% to 18.70%, and lignin from 6.15% to 1.43%, demonstrating the high thermal sensitivity of hemicellulose and cellulose during torrefaction. These changes align with literature reports that hemicellulose decomposes between 200–300°C, followed by partial cellulose degradation, while lignin shows slower decomposition (Jaya *et al*., 2021). The reduction in polysaccharides enhances the hydrophobicity of torrefied biomass, improving its storage stability and resistance to microbial attack. This aligns with findings that molecular composition changes enhance the suitability of corn stover for densification and energy applications, as hemicellulose loss reduces hygroscopicity, while retained cellulose and lignin contribute to mechanical strength in pellets (Nair et al., 2025; Jaya et al., 2021).

3.2 Changes in Physical Properties of Densified Pellets

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Densified/Pelletized Mass of Corn Stover

Table 4 presents data for densified pellets under varying torrefaction parameters. Calorific value (CV) ranged from 17.51 to 19.03 MJ/kg, MC from 1.42% to 8.90%, and mass from 0.67 to 0.89 kg.

Table 4: Experimental Design of the Densified/Pelletized MCS Samples

Reaction Temperature (deg. C)	Residence Time (Min)	Heating Rate (deg.C/Min)	CV (MJ/kg)	MC (%)	Mass (kg)
260	30	8.65	17.80	5.70	0.86
260	45	5.79	18.26	5.00	0.79
220	45	4.88	17.77	6.50	0.88
260	45	5.78	18.31	4.20	0.80
260	45	5.77	18.28	4.60	0.81
260	60	4.32	18.92	3.90	0.78
300	30	10.02	18.61	3.00	0.75
220	45	4.89	17.78	7.00	0.87
220	60	3.68	17.96	6.10	0.82
220	30	7.32	17.51	8.90	0.89
300	45	6.67	18.84	2.00	0.69
260	30	8.69	17.81	5.00	0.81
260	45	5.78	18.27	5.40	0.80
300	60	5.03	19.03	1.42	0.67
300	45	6.67	18.86	1.90	0.72
260	60	4.34	18.92	4.10	0.77
260	45	5.76	18.27	5.00	0.79

It can be observed from Table 4 that densification of torrefied MCS further enhanced energy density. Experimental results revealed that optimal torrefaction conditions (300°C, 60 min) yielded the highest CV of 19.03 MJ/kg. ANOVA and regression analyses indicated that reaction temperature, residence time, and heating rate significantly influenced CV, with interaction effects (AB, AC) contributing positively. These results suggest that densification combined with torrefaction synergistically improves the energy content of biomass. This is consistent with previous reports that torrefied biomass densification enhances fuel energy density and handling characteristics due to reduced moisture and increased carbon content (Inegbedion, 2022; Özyuğuran and Yaman, 2017). Torrefied and densified corn stover can serve as a high-quality pellet fuel for industrial applications, offering consistent energy output and ease of storage.

Moisture Content of Densified MCS

Table 5 illustrates the predicted versus actual MC trend.

Table 5: ANOVA and Fitness Analysis for the MC

Source	SS	df	MS	F-value	p-value	Condition	R^2	Adj. R^2
Model	57.17	2	28.58	145.17	< 0.0001	significant	0.9540	0.9474
A-Reaction Temperature	50.90	1	50.90	258.52	< 0.0001			
B-Residence time	6.27	1	6.27	31.82	< 0.0001			
Residual	2.76	14	0.1969					
Lack of Fit	2.03	12	0.1693	0.4670	0.8397	not significant		
Pure Error	0.7250	2	0.3625					
Cor Total	59.93	16						

ANOVA results in Table 5 reveal that both reaction temperature and residence time significantly reduce moisture content. High R^2 (0.9540) and adjusted R^2 (0.9474) indicate robust predictive performance. The linear model for moisture content is also highly significant, with an F-value of 145.17 and a p-value of < 0.0001 as depicted in Table 5. The R^2 value of 0.9540 and adjusted R^2 of 0.9474 confirm that 95.40% of the variation in MC is explained by the model (Zack, 2022). Significant factors include reaction temperature (A) and residence time (B), while the heating rate (C) was removed due to its insignificance (P-value > 0.05). The non-significant lack of fit validates the model's suitability for predicting MC under varying torrefaction conditions (Shari, 2022).

ANOVA for Mass of Densified MCS

Table 6 presents, ANOVA and fitness analysis for mass of densified MCS.

Table 6: ANOVA and Fitness Analysis for the Mass

Source	SS	df	MS	F-value	p-value	Condition	R^2	Adj. R^2
Model	0.0587	2	0.0294	111.50	< 0.0001	significant	0.9409	0.9325
A-Reaction Temperature	0.0496	1	0.0496	188.40	< 0.0001			
B-Residence time	0.0091	1	0.0091	34.60	< 0.0001			

Residual	0.0037	14	0.0003			
Lack of Fit	0.0032	12	0.0003	1.20	0.5421	not significant
Pure Error	0.0005	2	0.0002			
Cor Total	0.0624	16				

The ANOVA analysis Table 6 shows that reaction temperature and residence time significantly influence the mass of torrefied biomass. The model exhibits strong predictive reliability ($R^2 = 0.9409$, Adj. $R^2 = 0.9325$), indicating that higher temperatures and optimized residence times reduce biomass mass loss effectively (Boumanchar *et al*., 2019; Frost, 2024b; Zack, 2022).

Conclusions

This study evaluated the effects of torrefaction on the chemo-physical, structural, and energetic characteristics of densified corn stover with the aim of assessing its suitability for bioenergy applications. The findings demonstrate that torrefaction significantly upgraded the fuel quality of corn stover by altering its chemical composition, physical properties, and energy performance. Increasing torrefaction temperature and residence time resulted in higher carbon concentration, reduced hydrogen and oxygen contents, and lower O/C and H/C ratios, confirming a progressive shift toward coal-like characteristics. These changes translated into enhanced thermal stability, improved hydrophobicity, and increased resistance to biological degradation. Structural degradation of hemicellulose and cellulose further contributed to improved grindability and combustion behavior. Proximate analysis revealed marked reductions in moisture and volatile matter and a corresponding increase in fixed carbon, leading to substantial improvements in calorific value and overall energy density. Densification of torrefied material significantly improved bulk density, mechanical integrity, and handling properties, confirming the synergistic benefits of combining torrefaction with pelletization. Overall, torrefaction at moderate to high temperatures produced densified corn stover pellets with enhanced fuel properties suitable for combustion and co-firing applications.

Recommendations

Based on these findings, it is recommended that torrefaction be adopted as a pre-treatment step for upgrading corn stover prior to densification for bioenergy use, particularly in regions with abundant agricultural residues. Optimal torrefaction conditions should balance energy enhancement with mass yield to ensure process efficiency and economic viability. Future studies should focus on techno-economic assessments, life-cycle environmental impacts, and large-scale combustion or co-firing performance to support commercial deployment. Further research into binder optimization and long-term storage behavior of torrefied pellets under tropical conditions is also recommended to enhance practical implementation.

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