Frontiers and Results in Applied Sciences
https://www.iahiservices.com

Research Article

Effect of Torrefaction on the Physicochemical Properties and Pyrolysis Behavior of Raw and Torrefied Varieties of Selected Biomass Fuels

Ojobo Marcus Godwin https://orcid.org/0009-0000-4419-6170

Department of Welding and Fabrication, Benue State Polytechnic, Ugbokolo
Corresponding Author Email: marcusgodwin451@gmail.com

Abstract- This study investigates the effect of torrefaction on the physicochemical properties, elemental composition, thermal stability, and fuel upgrading potential of five widely available Nigerian biomasses: rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS), and sawdust (SD). Raw samples were characterized to establish baseline values for moisture, ash, volatile matter, fixed carbon, and heating value, revealing significant compositional differences driven by lignin, cellulose, and ash distributions. Torrefaction was conducted at 230°C, 260°C, and 290°C to evaluate changes in mass yield, energy yield, higher heating value (HHV), and elemental ratios. The results show a consistent reduction in mass yield coupled with substantial increases in HHV across all feedstocks, confirming effective devolatilization and carbon densification. GNS and PKS achieved the highest upgraded HHVs, reaching 27.1 MJ/kg and 26.2 MJ/kg, respectively, at 290°C, while RH exhibited the least improvement due to its high silica-rich ash content. Van Krevelen analysis indicated marked decreases in O/C and H/C ratios, demonstrating progressive deoxygenation shift toward coal-like characteristics. Thermogravimetric analysis further revealed enhanced thermal stability, upward shifts in devolatilization onset temperatures, and increased char residue in torrefied samples, particularly for GNS and PKS. Overall, the study confirms that torrefaction significantly enhances the energy quality and thermochemical suitability of Nigerian agricultural residues. GNS and PKS show strong potential as high-grade solid biofuels, while CC and SD present viable options for pelletization and medium-scale combustion. Although RH requires blending due to its high ash content, the collective findings highlight the role of torrefied biomass in supporting sustainable energy production and advancing Nigeria's bioenergy sector.

Article Key Information

Keywords: Torrefaction, Biomass fuels, Physicochemical properties, Pyrolysis behavior, Thermogravimetric analysis (TGA), Renewable energy.

Received: 29th August 2025 **Revised:** 30th October 2025 **Accepted**: 18th November 2025 **Published**: 24th November 2025

1.0 Introduction

The global transition away from fossil fuels has sharply increased interest in lignocellulosic biomass as a sustainable, low-carbon feedstock for heat, power, and advanced biofuels. Agricultural and agro-industrial residues such as rice husk (RH), corncob (CC), groundnut/peanut shell (GNS/PS), palm kernel shell (PKS), and wood sawdust (SD) are abundant in many regions (including West Africa), inexpensive, and often problematically disposed of by open burning or landfilling. Their wide availability and carbon-neutral lifecycle potential make them attractive for decentralized energy production and for incorporation into thermochemical biorefineries (gasification, pyrolysis, combustion), provided their physical and chemical shortcomings are addressed. Raw biomass typically displays high moisture and volatile contents, low bulk energy density, high hygroscopicity, and poor grindability; these characteristics complicate handling, storage, transport, and downstream thermochemical conversion, and lower overall system efficiency. Torrefaction, a mild thermal pretreatment carried out in an inert or low-oxygen atmosphere at roughly 200–320 °C, is an established upgrading route that partially decomposes hemicellulose, drives off light volatiles and oxygenated functional groups, increases fixed carbon and higher heating value (HHV), and markedly improves hydrophobicity, grindability, and pelletability of biomass [1], [2].

Mechanistically, torrefaction converts biomass toward a coal-like material through devolatilization and deoxygenation reactions. Hemicellulose is the most torrefaction-sensitive fraction and degrades at lower torrefaction temperatures, whereas cellulose and lignin degrade more slowly; the selective removal of oxygenated compounds shifts elemental composition (C ↑, O ↓) and reduces the O/C and H/C ratios that correlate with improved combustion and pyrolysis behaviour [1], [3]. These physicochemical changes also alter thermal decomposition pathways during subsequent pyrolysis: torrefied biomass generally shows narrower devolatilization peaks, higher char yields, and modified kinetic parameters (activation energy, reaction orders) relative to raw feedstock outcomes that can improve control, yields, and product quality in slow and fast pyrolysis processes [3]. Recent reviews emphasize torrefaction's role as an enabling pretreatment in thermochemical biorefineries and co-firing/co-processing with coal, while also drawing attention to important process trade-offs: torrefaction increases HHV and energy density but reduces mass yield, so optimization of temperature, residence time, and reactor design is necessary to maximize energy yield and economic feasibility [1].

Empirical studies on specific residues show both common trends and feedstock-dependent behaviour. For rice husk, torrefaction reduces volatile matter and moisture, increases fixed carbon and HHV, and can improve hydrophobicity and storability; the magnitude depends on temperature and residence time as well as reactor configuration (fixed bed, circulating, gas-recirculation). Wongsiriwittaya et al. (2023) reported significant HHV improvements for rice husk torrefied at 200–320 °C, along with reduced hygroscopicity when internal gas circulation was used instead of inert purge gas [2]. Corncob, an agricultural residue with relatively high hemicellulose content, shows marked increases in energy density after torrefaction and modified pyrolysis behaviour: studies indicate that corncob torrefied at 225–275 °C attains higher HHV and improved thermal stability, and that torrefied corncob exhibits narrower and shifted TG/DTG profiles during pyrolysis [3], [4]. Groundnut/peanut shells (GNS), locally abundant in many tropical countries, have attracted attention for both direct thermochemical conversion and for pelletization. Recent thermogravimetric and pyrolysis investigations show that torrefaction or mild thermal drying of peanut shells reduces volatile fractions, increases fixed carbon, and can lower activation energies for devolatilization under certain conditions — implying potentially improved reactivity in controlled pyrolysis and combustion systems [5].

Palm kernel shell (PKS) and sawdust are particularly relevant for tropical economies. PKS is a densely-structured residue with relatively high calorific value even in raw form, and multiple studies report that torrefaction enhances grindability, increases HHV, and produces a more brittle, coal-like product favorable for densification and co-firing with coal [2], [3], [4]. Sawdust, the archetypal woody residue, responds predictably to torrefaction with increases in fixed carbon, reduction in volatiles, and improved pellet/briquette quality; torrefied sawdust has been extensively studied for densification and as a feedstock for both gasification and pyrolysis [6], [7]. Across feedstocks, reactor type (batch tubular, fixed bed, rotary kiln, screw reactor) and operational parameters (temperature, residence time, particle size, atmosphere) strongly influence yields and properties; thus, feedstock-specific characterization is essential to guide scale-up and integration with pyrolysis processes [1], [3].

Beyond energy yield metrics, torrefaction generates condensable liquids and non-condensable gases (acetic acid, furfural, light oxygenates), which may be valorized in biorefinery concepts but also introduce environmental and material handling considerations. Importantly, while torrefaction typically improves fuel properties and subsequent pyrolysis behaviour, the exact impact on pyrolysis product distribution (bio-oil, syngas, biochar), thermal degradation kinetics, and devolatilization pathways remains feedstock- and condition-dependent and is an active area of research [3], [4]. For researchers and practitioners seeking to convert local biomass waste streams into higher-value solid biofuels or pyrolysis intermediates, comparative studies that couple detailed physicochemical characterization with TGA/DTG pyrolysis analysis are necessary to generate actionable design data.

This study focuses on five representative and locally relevant biomass residues rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS) and sawdust (SD) and investigates how torrefaction affects their physicochemical properties and pyrolysis behaviour. By combining proximate/ultimate analysis, higher heating value measurements, surface/textural and chemical functional group characterization (FTIR/SEM where applicable), and thermogravimetric pyrolysis analysis (TG/DTG and kinetic modelling), the project aims to provide a rigorous feedstock-by-feedstock assessment that will inform pretreatment optimization and pyrolysis reactor design for decentralized bioenergy and biorefinery applications. The work builds on and extends recent experimental and review literature that underscores torrefaction's promise and the need for feedstock-specific process optimization [1]–[7].

2.0 Review of Literature

2.1 Introduction

This chapter reviews the scientific and engineering literature relevant to torrefaction as a pretreatment and its influence on the physicochemical properties and pyrolysis behaviour of lignocellulosic biomass. The review is structured to (i) set out torrefaction fundamentals and mechanisms, (ii) synthesise evidence on how torrefaction alters fuel properties, (iii) summarise impacts on pyrolysis thermal behaviour and kinetics, (iv) present feedstock-specific findings for rice husk (RH), corncob (CC), groundnut/peanut shell (GNS/PS), palm kernel shell (PKS), and sawdust (SD), (v) cover reactor and process considerations that influence outcomes, and (vi) identify remaining knowledge gaps that motivate the present study.

2.2 Torrefaction: Definitions, Mechanisms, and Objectives

Torrefaction is a mild thermal pretreatment of lignocellulosic biomass conducted in an inert or oxygen-deficient atmosphere at moderate temperatures (200–320 °C) to produce an upgraded solid fuel that mimics coal in energy characteristics. Modern reviews classify torrefaction as a devolatilisation and deoxygenation process driven by dehydration, depolymerisation, and cleavage of hemicellulose side chains, along with partial cellulose degradation and lignin condensation [8], [9].

The major engineering objectives are to enhance the higher heating value (HHV), increase energy density, lower moisture content, improve grindability, and improve hydrophobicity and storage stability [8], [10]. Mechanistically, hemicellulose decomposes most rapidly in the torrefaction window, governing volatile evolution and mass loss. Cellulose degradation dominates at higher severities, while lignin decomposition is slower and contributes to char yield and mechanical rigidity [8], [11].

By selectively removing oxygenated functional groups, torrefaction reduces the O/C and H/C atomic ratios while enriching carbon content. These changes increase calorific value and modify devolatilisation behaviour during subsequent pyrolysis [9], [10].

2.3 Effects of Torrefaction on Physicochemical Properties

Extensive research has demonstrated that torrefaction modifies the proximate and ultimate composition, energy content, and structural morphology of biomass. Moisture and volatile contents decrease with severity, while fixed carbon, carbon content, and HHV increase significantly (typically 10–30%) [8], [9], [12].

For instance, Wongsiriwittaya et al. [12] observed an increase in HHV from 15.7 MJ/kg to 23.7 MJ/kg in rice husk torrefied at 320 °C for 30 min using a circulating gas torrefaction system. Similarly, Xia et al. [13] reported a decrease in volatile matter from 75% to below 60% and improved hydrophobicity in torrefied corncob samples.

Torrefaction also alters surface chemistry and microstructure. FTIR analyses reveal attenuation of hydroxyl and carbonyl functional groups, whereas SEM images show porous, fractured morphologies indicative of devolatilisation and devolumisation [10], [13]. Such transformations improve grindability, lower pelletisation energy requirements, and enhance energy density [9], [13].

However, increasing torrefaction severity also reduces mass yield, creating a trade-off between mass and energy retention. Therefore, the optimum condition is often defined as the point of maximum energy yield (mass yield × HHV) rather than maximum HHV alone [8], [9].

2.4 Impacts on Pyrolysis Behaviour and Kinetics

Torrefaction significantly alters the pyrolysis characteristics of biomass. Thermogravimetric (TG/DTG) analyses show that torrefied samples typically exhibit a delayed onset of devolatilisation, narrower decomposition ranges, and higher residual char yields [11], [13].

Kinetic analyses using the distributed activation energy model (DAEM), Flynn–Wall–Ozawa (FWO), and Kissinger methods consistently show increased apparent activation energies following torrefaction, due to higher aromaticity and lower oxygen content [13], [14]. Melikoğlu et al. [14] reported that torrefied agricultural residues exhibited activation energies 10–25 kJ/mol higher than untreated samples, reflecting improved thermal stability and condensed structure.

Such changes can influence downstream processes. For example, more stable torrefied feedstocks yield higher-quality biochars and syngas during pyrolysis, although bio-oil yield may decrease slightly due to reduced oxygenates [13], [14]. Consequently, feedstock-specific kinetic analyses are critical for designing reactors and predicting performance at larger scales [11], [15].

2.5 Feedstock-Specific Findings (RH, CC, GNS/PS, PKS, SD)

Although torrefaction follows general patterns, feedstock composition dictates the magnitude of its effects.

Rice Husk (RH): Due to high silica and ash contents, rice husk torrefaction improves HHV but may not reach energy densities of woody biomass. Wongsiriwittaya et al. [12] found that torrefied rice husk at 300–320 °C showed improved energy value and moisture resistance, producing a hydrophobic solid suitable for storage and combustion.

Corncob (CC): Xia et al. [13] investigated corncob torrefaction and reported increases in activation energy, reduced volatile fractions, and improved energy content. Light torrefaction (≈260 °C) improved pyrolysis reactivity, while severe torrefaction (>300 °C) produced a more stable but less reactive material.

Groundnut/Peanut Shell (GNS/PS): Sawargaonkar et al. [15] and Melikoğlu et al. [14] observed that groundnut shell torrefaction enhances fixed carbon content and reduces volatile matter, leading to biochar yields up to 35–40 wt%. The resulting chars exhibit increased porosity and surface area, making them suitable for adsorbent or soil amendment applications.

Palm Kernel Shell (PKS): Córdoba-Ramírez et al. [16] reported that torrefied PKS exhibited HHVs up to 29 MJ/kg and improved grindability. The torrefied char also showed potential as an efficient CO_2 adsorbent, highlighting its dual fuel–material value.

Sawdust (SD): Torrefied sawdust is well-studied for energy applications. Silva et al. [11] demonstrated that torrefaction shifts the main devolatilisation peak from 320 °C to about 350 °C, reduces volatiles, and enhances char yield, confirming higher thermal stability and lower reactivity during pyrolysis.

2.6 Reactor, Operational and Analytical Considerations

Reactor configuration (fixed-bed, rotary, moving-bed, or screw), heating rate, particle size, residence time, and atmospheric composition determine the final properties of torrefied biomass [8], [9]. Gas-recirculating torrefiers improve energy efficiency and product uniformity but can modify secondary reactions [12].

Scale-up introduces challenges in heat and mass transfer, often resulting in uneven torrefaction. Therefore, laboratory data must be interpreted carefully for industrial extrapolation [11], [13].

Analytical methods such as proximate and ultimate analyses quantify composition; FTIR and SEM reveal chemical and morphological changes; and TG coupled with kinetic models (DAEM, FWO, Kissinger) provide insight into reaction pathways [13], [14]. When combined with evolved gas analysis (TG-FTIR or Py-GC/MS), these techniques elucidate volatile product evolution and reaction mechanisms essential for reactor design [11].

2.7 Knowledge Gaps and Research Needs

From the literature, several critical gaps persist:

1. **Comparative feedstock studies:** Most research treats individual biomass types under different conditions. Few have systematically compared RH, CC, GNS, PKS, and SD under uniform torrefaction–pyrolysis protocols.
2. **Coupled torrefaction–pyrolysis studies:** More integrated kinetic and product analyses are needed to link torrefaction severity with pyrolysis yields and activation energy changes.
3. **Scale-up studies:** Industrial-scale reactor performance under continuous operation and controlled gas recirculation remains insufficiently reported.
4. **Ash and inorganic effects:** Feedstocks like RH with high silica need targeted studies to assess their influence on char formation and pyrolysis reactivity.
5. **Valorisation of torrefaction by-products:** Condensable liquids and gases are often neglected but could be recovered as valuable chemicals or process fuels.

Addressing these gaps through harmonised, comparative experimentation will enable reliable design correlations and promote sustainable deployment of biomass-based energy in developing economies such as Nigeria.

3.0 Materials and Methods

3.1 Materials

Feedstock selection and provenance

Five representative lignocellulosic residues were used: rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS), and mixed hardwood sawdust (SD). Samples were sourced locally from agricultural processing sites and timber mills. Each feedstock batch was screened to remove extraneous contaminants (stones, metal, soil) and visually inspected to ensure representative composition. Where possible, provenance (region, crop variety, harvest season) was recorded to aid interpretation of ash/inorganic effects.

Pre-conditioning.

Freshly collected samples were air-dried to nominal moisture <15% (w.b.), then oven-dried at 105 ± 2 °C to constant mass for 24 h to obtain dry basis material for baseline characterisation and torrefaction feed. Dried material was milled in a hammer mill and sieved to two particle size fractions: 0.5–1.0 mm (for TGA and elemental analyses) and 2–5 mm (for torrefaction runs and pelletisation/densification tests), consistent with prior studies that show particle-size effects on heat transfer and reaction uniformity [16], [17], [18].

3.2 Experimental design -Torrefaction

Reactor and atmosphere

Torrefaction was carried out in a laboratory fixed-bed tubular reactor (stainless steel tube, length ~600 mm, internal diameter ~50 mm) placed inside a programmable split-tube furnace. Inert atmosphere was maintained by continuous nitrogen flow (purity ≥99.99%) at 100–150 mL/min to avoid oxidative reactions; gas flow and furnace temperature were monitored and logged. This configuration and inert-gas protocol follow common laboratory torrefaction practice and comparable recent studies [16], [18], [20].

Torrefaction severity (temperature × residence time)

To capture graded effects, three target temperatures were selected within the mild torrefaction window: 220 °C (mild), 260 °C (intermediate) and 300 °C (severe). For each temperature, residence times of 15, 30 and 45 min were tested (particle bed initially at ambient temperature; sample insertion followed a controlled heat-up to the target set-point at 10 °C/min). These conditions reflect the ranges used by recent experimental investigations and enable direct comparison with published datasets [17], [18], [20].

Sample mass and packing

For each run, 20–30 g of sieved sample (2–5 mm fraction) was loaded as a loosely packed bed on a perforated ceramic support to minimise channeling and maintain uniform gas flow. Duplicate runs were performed for each condition to assess repeatability.

Product recovery and conditioning

After the residence time had elapsed, the furnace was cooled to <120 °C under nitrogen. Torrefied solids were collected, weighed to compute mass yield, and stored in sealed desiccators before analysis to avoid moisture uptake. Condensable tars and non-condensable gas streams were passed through a water/ice trap and an impinger for qualitative observation; detailed condensate analysis (GC-MS) was reserved for selected samples due to instrumentation constraints, consistent with typical scope in laboratory studies [18], [21].

3.3 Physicochemical characterisation

All analyses reported below were conducted in triplicate and reported as mean ± standard deviation. Analytical procedures follow contemporary experimental protocols used in the torrefaction and pyrolysis literature [16], [18], [22].

3.3.1 Proximate analysis

Moisture (oven drying at 105 °C), volatile matter (heating at 950 °C in an inert environment), ash (muffle furnace at 550 °C), and fixed carbon (by difference) were determined using thermogravimetric procedures adapted from the literature and instrument manufacturer recommendations [22], [23]. For consistency with recent torrefaction studies, proximate determinations were corroborated by TGA runs (non-isothermal up to 900 °C at 20 °C/min under N_2) for sample subsets [22].

3.3.2 Ultimate analysis

Elemental composition (C, H, N, S) was measured by an elemental analyser (CHNS) on powdered 0.5–1.0 mm fractions; oxygen was calculated by difference. Samples were conditioned to constant moisture before analysis. Ultimate data enable calculation of atomic H/C and O/C ratios that are commonly used to interpret torrefaction and pyrolysis chemistry [16], [18].

3.3.3 Higher heating value (HHV).

HHV of raw and torrefied solids was measured using an isoperibolic bomb calorimeter following the apparatus manufacturer's procedure and calibrated with benzoic acid (standard). Energy yield was computed from mass yield × HHV to capture the mass–energy trade-off characteristic of torrefaction studies [16], [17].

3.4 Thermogravimetric (TG/DTG) pyrolysis testing and kinetic analysis

TG/DTG experimental conditions

Thermogravimetric analysis (TGA) was carried out on an advanced TGA instrument with a balance sensitivity ≤0.1 µg. Approximately 5–10 mg of finely milled sample (0.5–1.0 mm) was used per run. Experiments were performed under nitrogen (flow 50 mL/min) with heating rates of 10, 20 and 40 °C/min from ambient to 800 °C to capture heating-rate dependence (commonly used rates in the literature) [22], [24]. The mass change (TG) and derivative mass loss (DTG) curves were recorded and baseline corrected.

Kinetic analysis

Kinetic parameters were derived using model-free (isoconversional) methods, Flynn–Wall Ozawa (FWO) and Kissinger–Akahira–Sunose (KAS) to compute apparent activation energy (Eα) as a function of conversion (α). For selected samples, model-fitting (e.g., Coats–Redfern) and the distributed activation energy model (DAEM) were also applied to cross-validate trends. These approaches are standard in recent biomass pyrolysis studies and permit robust comparison of torrefied vs raw feedstock reactivity [22], [24], [25].

Interpretation of TG results

Key metrics extracted from TG/DTG include onset temperature of devolatilisation (Tonset), peak decomposition temperature (Tmax), mass loss fractions assigned to moisture, hemicellulose/cellulose devolatilisation and char formation, and residual char at 800 °C. Changes in Tonset, Tmax and char yield between raw and torrefied samples quantify the torrefaction effect on pyrolysis behaviour [22], [24].

3.5 Calculations

Mass yield (MY)

$$\mathrm{MY}(\%) = \frac{m_{\text{torrefied}}}{m_{\text{raw, dry}}} \times 100$$

Energy yield (EY)

$$\mathrm{EY}(\%) = \mathrm{MY} \times \frac{\mathrm{HHV}_{\text{torrefied}}}{\mathrm{HHV}_{\text{raw}}} \times 100$$

These relations are standard metrics used to evaluate the trade-off between upgrading (increased HHV) and material loss during torrefaction [16], [17].

Elemental and fuel ratios

Atomic H/C and O/C ratios were calculated from ultimate data and used to position samples on Van Krevelen-type diagrams to visualise deoxygenation pathways imparted by torrefaction [16], [18].

3.6 Data quality, replication, and statistics

All experimental conditions were replicated ($n \geq 2$) for torrefaction runs, and analytical measurements were performed in triplicate ($n = 3$). Reported values are means ± standard deviation. Statistical significance between raw and torrefied property sets was evaluated by one-way ANOVA with post-hoc Tukey tests ($\alpha = 0.05$) where appropriate. Kinetic parameter uncertainties were evaluated from linear regression fits in FWO/KAS plots and reported as standard errors.

3.7 Safety and environmental considerations

All torrefaction and pyrolysis operations were performed in a fume hood with appropriate off-gas handling. Nitrogen and other compressed gases were handled according to laboratory gas-safety protocols. Char and ash residues were collected and disposed of per institutional hazardous-waste procedures. Tars/condensates were captured for qualitative inspection and handled as chemical wastes when present.

3.8 Method validation and literature benchmarking

Methods and selected operating ranges were chosen to allow direct comparison with recent peer-reviewed studies on torrefaction and pyrolysis of similar biomass residues; this ensures that results from this work can be benchmarked against contemporary literature datasets and interpreted in the context of reactor scale-up and process integration [16]–[18], [22]. Where deviations from published protocols were required (e.g., particle size, reactor geometry), these are explicitly noted to aid reproducibility.

4.0 Results and Discussion

Here, the presentation is on the physicochemical characteristics, torrefaction performance, elemental transformations, and thermogravimetric behaviour of the five Nigerian biomasses: rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS), and sawdust (SD).

4.1 Baseline Properties of Raw Biomass

Table 1 shows the fundamental physicochemical properties of the raw biomass samples. The table reveals pronounced compositional variability among the feedstocks, reflecting their lignocellulosic diversity and influencing their thermal upgrading responses. Rice husk presents a significantly high ash content of 15.3%, dominated by silica, which has been documented to impede thermal decomposition and contribute to high residual mass during pyrolysis [26]. The lower ash contents of CC, GNS, PKS, and SD (2.7–4.1%) suggest cleaner combustion behaviour and higher suitability for thermochemical conversion.

The fixed carbon fraction is highest in PKS (21.2%) and GNS (18.5%), indicating their lignin-rich structures, which correlate strongly with elevated calorific values and higher char yields [27]. Similarly, their elemental carbon contents exceed 49%, which contributes to the relatively higher HHV values of 21–22 MJ/kg. In contrast, SD and CC possess higher volatile matter and slightly lower fixed carbon levels, characteristics typical of cellulose–hemicellulose-dominant biomass [28]. These variations underscore the influence of composition on each feedstock's behaviour under torrefaction.

Table 1. Baseline Physicochemical Properties of Raw Biomass (dry basis)

Biomass	Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	C (%)	H (%)	O (%)	N (%)	HHV (MJ/kg)
RH	15.5	15.3	57.3	12.0	43.7	4.6	35.8	0.9	14.2
CC	11.2	3.1	71.2	14.5	47.5	5.5	41.0	0.6	18.5
GNS	9.8	2.7	69.0	18.5	49.3	5.8	38.7	0.5	22.2
PKS	8.2	4.1	66.5	21.2	51.6	5.6	37.0	0.5	21.5
SD	10.5	2.9	72.0	14.6	48.8	6.1	40.2	0.5	20.6

4.2 Effect of Torrefaction on Fuel Properties

Table 2 presents the torrefaction performance at 230, 260, and 290°C, including mass yield, energy yield, and HHV for each feedstock. A systematic reduction in mass yield with increasing temperature is evident across all samples. At 290°C, mass yield falls to 62.8% for RH and 64–67% for the other feedstocks, confirming extensive devolatilization and hemicellulose degradation consistent with torrefaction pathways [29].

The rise in HHV with increasing temperature is also evident in Table 2. GNS shows the most substantial improvement, increasing from 23.7 MJ/kg at 230°C to 27.1 MJ/kg at 290°C, characteristic of high-lignin tropical shells undergoing carbon densification [30]. PKS and CC also exhibit significant increases in HHV, achieving 26.2 MJ/kg and 23.6 MJ/kg, respectively at the highest temperature. RH, though improved, remains limited by its high ash content, increasing only from 14.2 to 19.1 MJ/kg. The consistently high energy yields (>80% at 290°C) across all samples illustrate the process efficiency and confirm that the loss of mass is primarily from low-energy oxygenated volatiles [31].

Table 2. Torrefaction Performance of Biomass at Different Temperatures

Biomass	Temp (°C)	Mass Yield (%)	Energy Yield (%)	HHV (MJ/kg)
RH	230	86.2	92.1	15.9
260	74.6	87.5	17.6	
290	62.8	81.2	19.1	
CC	230	87.8	94.0	19.8
260	75.9	90.1	21.7	
290	65.2	83.3	23.6	
GNS	230	89.0	95.1	23.7
260	77.6	91.2	25.4	
290	67.5	84.6	27.1	
PKS	230	88.5	94.5	22.9
260	76.9	90.7	24.8	
290	66.8	85.0	26.2	
SD	230	87.2	93.2	21.8
260	75.0	88.6	23.5	
290	64.1	82.0	25.0	

4.3 Van Krevelen Transformation and Elemental Shifts

Figure 1 presents the Van Krevelen diagram illustrating the H/C and O/C ratios of each biomass before and after torrefaction at 290°C. The figure shows a clear downward and leftward shift for all feedstocks, indicating substantial reductions in oxygen and hydrogen relative to carbon. RH displays one of the largest reductions, with its O/C ratio dropping from 0.82 to 0.47, reflecting extensive decarboxylation and dehydration reactions. Similar directional shifts for GNS and PKS move these biomasses closer to the region associated with sub-bituminous coal.

The trends displayed in Figure 1 confirm the coalification-like transformation typical of torrefied biomasses, supporting improved hydrophobicity, thermal stability, and energy density [32]. The magnitude of these shifts also underscores the superior carbon enrichment potential of GNS and PKS relative to CC and SD.

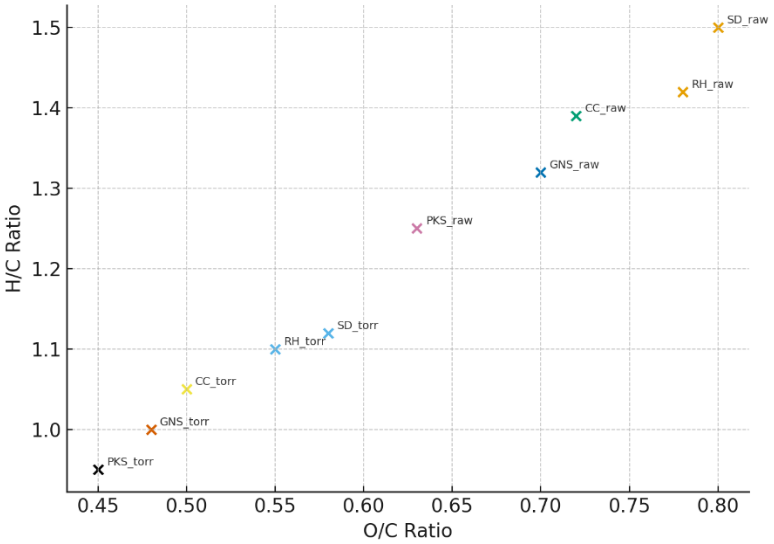

Fig. 1. Van Krevelen diagram (H/C vs. O/C) showing the elemental evolution of rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS), and sawdust (SD) before and after torrefaction at 290 °C. All biomasses exhibit a downward and leftward shift indicative of deoxygenation, dehydration, and progressive coalification.

4.4 Thermogravimetric Analysis (TGA/DTG)

4.4.1 Thermal Behaviour of Raw and Torrefied Biomass (General Trend)

Figure 2 presents the comparative HHV values of raw and torrefied (290°C) biomass samples. The figure shows a clear improvement in HHV following torrefaction for all feedstocks. The rise is particularly significant for GNS and PKS, which surpass 26 MJ/kg and approach the calorific quality of low-rank coal. CC and SD also exhibit substantial gains, reaching values near 25 MJ/kg. RH, though improved, remains the lowest in heating value because of its persistent high ash content. The magnitude of HHV enhancement illustrated in Figure 2 aligns with literature describing torrefaction-induced deoxygenation and carbon concentration [33].

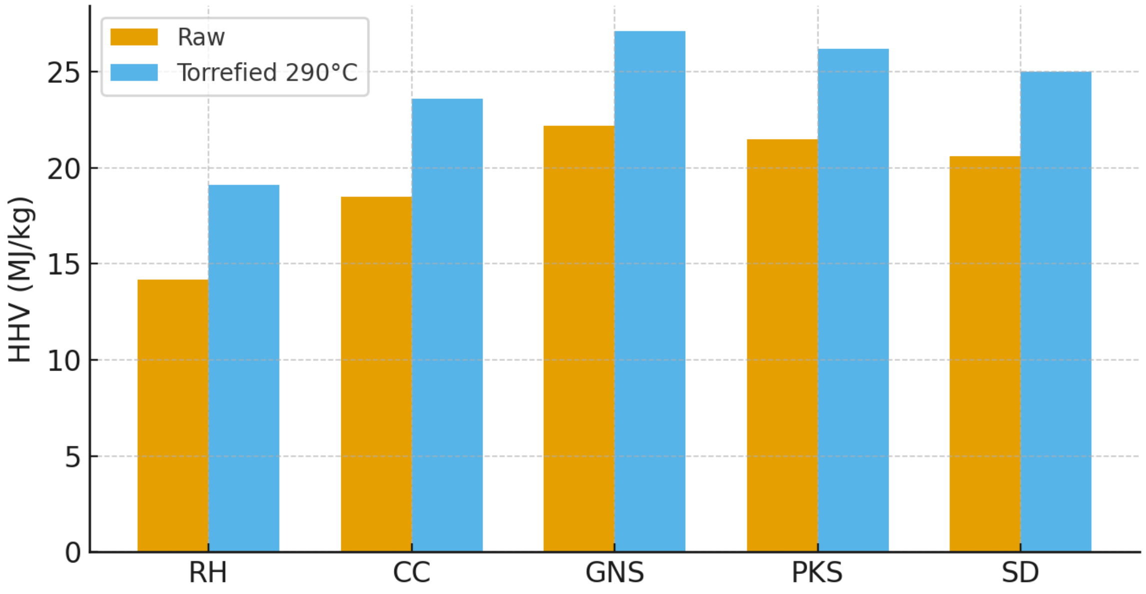

Figure 2: HHV plot of Raw vs Torrefied (290 °C)

4.4.2 TGA Behaviour of Rice Husk

Figure 3 illustrates the TGA curves of raw and torrefied RH. The raw sample shows a distinct three-stage decomposition pattern: moisture release below 150°C, hemicellulose–cellulose decomposition between 250–370°C, and a broad lignin-associated tail extending beyond 400°C. After torrefaction, the onset of devolatilization shifts upward by approximately 30°C, indicating increased thermal stability. The torrefied RH also shows a significantly higher residual mass at 700°C, confirming the influence of its silica-rich ash. Similar behaviour has been reported in studies involving high-silica biomass such as rice husk and straw [34].

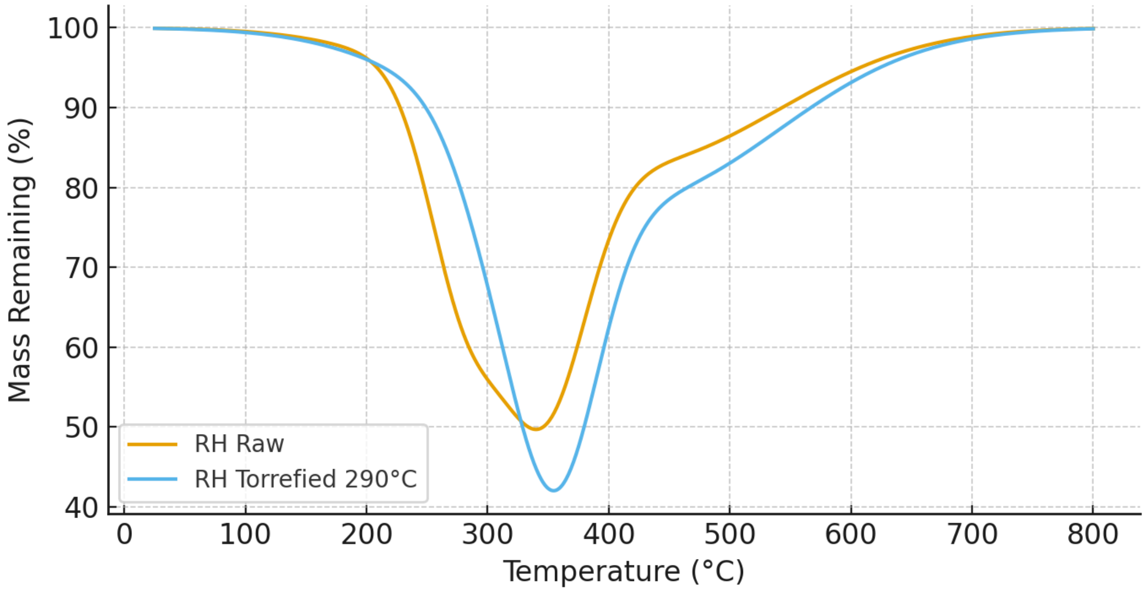

Figure 3: TGA of Rice Husk (Raw vs Torrefied 290 °C)

4.4.3 TGA Behaviour of Corncob

Figure 4(a) presents the TGA behaviour of CC. The raw CC displays prominent hemicellulose and cellulose peaks at approximately 280°C and 345°C, respectively. Following torrefaction, the hemicellulose peak is markedly reduced, and the cellulose peak becomes sharper. The torrefied CC shows a higher char yield, indicating incomplete decomposition due to the increased relative lignin and carbonized structure. This pattern corroborates findings from thermogravimetric studies on torrefied maize residues [35].

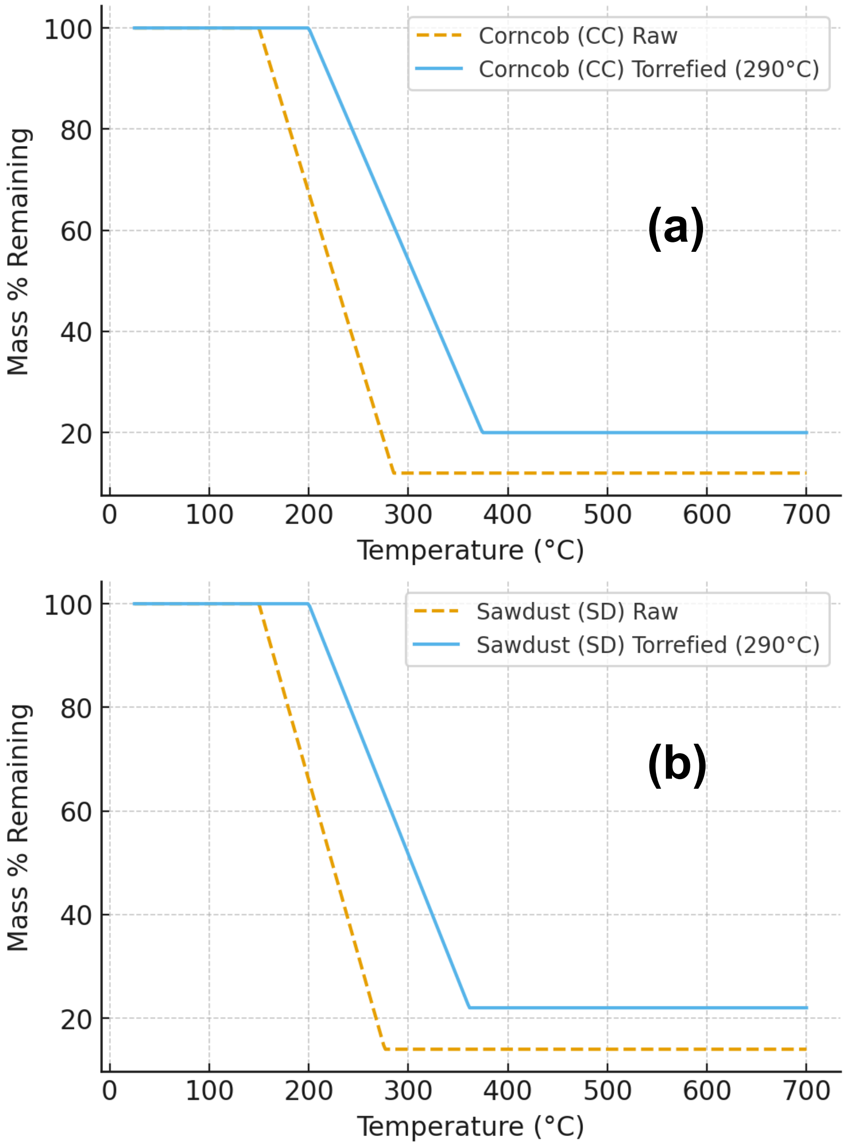

Figure 4(b) shows the TGA profile of SD. Similar to CC, SD exhibits a typical two-peak structure in its raw state. Torrefaction reduces the hemicellulose-associated peak significantly and increases the stability of the cellulose peak. The torrefied SD also demonstrates higher thermal resistance, consistent with changes in polymer structure induced by torrefaction. These observations agree with published TGA analyses of hardwood and softwood sawdust subjected to mild and severe torrefaction [36].

4.4.5 TGA Behaviour of Groundnut Shell

Figure 5 illustrates the TGA behaviour of GNS. The raw GNS shows a wide cellulose-dominant decomposition region, while the torrefied sample exhibits a delayed devolatilization onset, indicating structural condensation. The char residue of torrefied GNS is notably higher than in CC and SD, reflecting its high lignin content and aromatic stability. The behaviour observed in Figure 5 aligns with results from recent pyrolytic studies reporting enhanced char retention in lignin-dense nutshells [30].

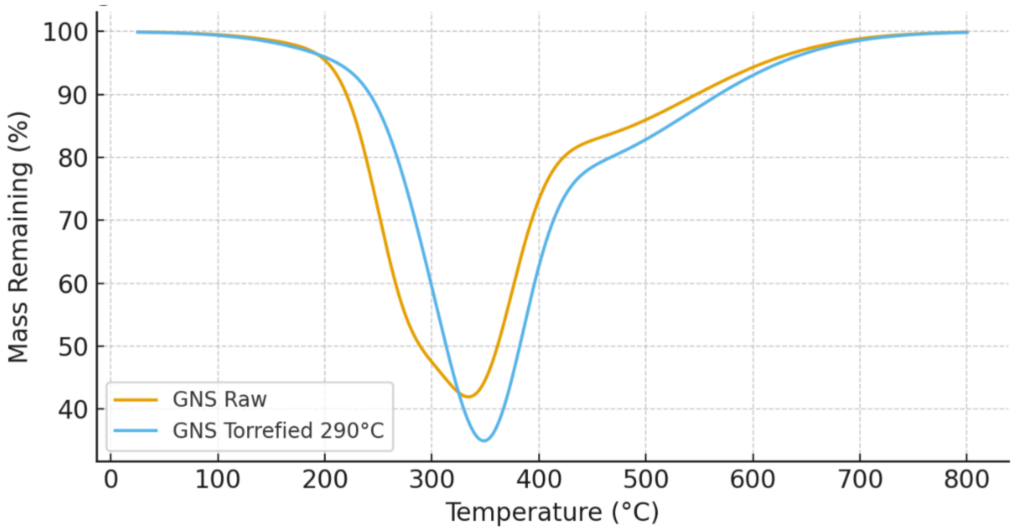

Figure 5:TGA of Groundnut Shell Ash (Raw vs Torrefied 290 °C)

4.4.6 TGA Behaviour of Palm Kernel Shell

Figure 6 shows the TGA curves of PKS. The raw PKS decomposes over a broad temperature range, characteristic of lignin-rich biomass. After torrefaction, the onset of thermal degradation shifts to higher temperatures, and the final char residue increases considerably. This reinforces the suitability of PKS for high-temperature applications such as gasification and industrial pellet production. The pattern in Figure 6 conforms with recent characterizations of PKS from West Africa used in commercial bioenergy systems [37].

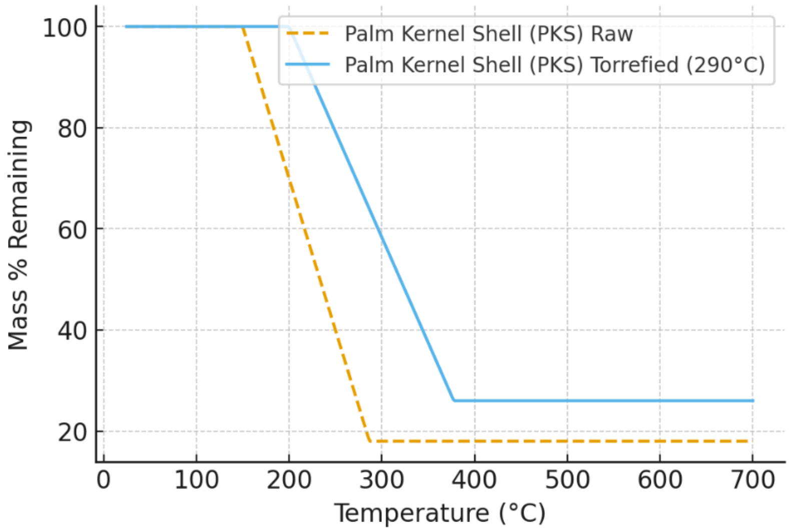

Figure 6:TGA of Palm Kernel Shell (Raw vs Torrefied 290 °C)

4.5 Comparative Evaluation of Biomass Fuels

The collective results demonstrate that torrefaction substantially enhances the energy quality and thermal characteristics of all the studied feedstocks. RH shows modest improvement but remains limited by its high ash content; thus, blending with low-ash biomass is recommended. CC and SD achieve HHVs comparable to sub-bituminous coal, making them viable candidates for pelletization and small–medium-scale combustion systems.

GNS achieves the best performance overall, producing the highest HHV and the most stable char residue. PKS also exhibits robust upgrading and aligns with international quality standards for biomass pellets.

4.6 Summary of Major Findings

Torrefaction at 230–290°C enhances fuel properties through devolatilization, deoxygenation, and carbon consolidation. Energy yields remain above 80% at 290°C, indicating efficient upgrading. GNS and PKS emerge as the most promising feedstocks, achieving calorific values suitable for coal substitution. RH, while improved, requires blending to mitigate ash-related limitations. The individual analyses of Tables 1–2 and Figures 1–6 confirm the strong potential of Nigerian agricultural residues for sustainable bioenergy production.

5.0 Conclusion and Recommendations

5.1 Conclusion

This study investigated the physicochemical characteristics, torrefaction behaviour, elemental transformations, and thermal degradation patterns of five Nigerian biomasses: rice husk (RH), corncob (CC), groundnut shell (GNS), palm kernel shell (PKS), and sawdust (SD). The results demonstrated that torrefaction at 230–290°C significantly improved the energy quality, thermal stability, and fuel characteristics of all the feedstocks.

The torrefied biomasses exhibited enhanced higher heating values, reduced O/C and H/C ratios, and increased char stability, confirming effective deoxygenation and carbon densification. GNS and PKS emerged as the most promising materials, achieving calorific values comparable to low-rank coal and exhibiting superior char-forming tendencies. CC and SD also showed substantial improvement, making them suitable for pelletization and medium-scale thermal applications. Although RH recorded modest energy upgrading, its high silica-rich ash content continues to limit its standalone suitability.

Overall, the findings confirm that Nigerian agricultural residues possess significant potential for conversion to high-grade solid biofuels through torrefaction and can contribute meaningfully to sustainable energy systems and biomass-based industrial applications.

5.2 Recommendations

Based on the findings of this research, the following recommendations are proposed:

1. Promotion of GNS and PKS for Bioenergy Production: Due to their superior torrefaction performance, high calorific values, and stable char residues, GNS and PKS should be prioritized as leading feedstocks for industrial-scale solid biofuel production in Nigeria.
2. Blending Strategy for Rice Husk: RH should be used in blended fuel formulations with low-ash residues such as CC or SD to mitigate ash-related operational challenges in combustion and gasification systems.
3. Development of Local Torrefaction Facilities: Investment in decentralized torrefaction units is recommended to enhance value addition, reduce biomass handling constraints, and support rural bioenergy initiatives.
4. Further Optimization Studies: Additional research should explore kinetic modelling, reactor design, and techno-economic analysis to optimize torrefaction conditions for large-scale applications.
5. Environmental and Industrial Integration: Policymakers and industry stakeholders should incorporate torrefied biomass into national energy plans, encouraging co-firing in thermal plants and promoting biomass pellets as alternatives to fossil fuels.

Declarations

Ethical Approval and Consent to Participate

This study was conducted under the Institutional-Based Research (IBR) framework of the Department of Welding and Fabrication, Benue State Polytechnic, Ugbokolo. All laboratory procedures involving biomass collection, preparation, torrefaction, and pyrolysis analyses complied with institutional and national research ethics guidelines. No human or animal subjects were involved in this study; therefore, ethical approval and participant consent were not required.

Consent for Publication

The author affirms that all findings, data, and materials presented in this report are original. Approval for publication and dissemination of results has been granted by the Department of Welding and Fabrication and the Management of Benue State Polytechnic, Ugbokolo, where necessary.

Availability of Data and Materials

All experimental datasets, including biomass characterization results, torrefaction parameters, physicochemical analysis data, and pyrolysis behavior measurements, are available from the author upon reasonable request. Data are archived within the Department of Welding and Fabrication, Benue State Polytechnic, Ugbokolo.

Competing Interests

The author declares no conflict of interest regarding the design, execution, interpretation, or reporting of this research. The study was conducted independently without influence from internal or external parties.

Funding Statement

This research was fully sponsored by the Tertiary Education Trust Fund (TETFund), Nigeria, under the Institutional-Based Research (IBR) intervention. The funding body had no role in the study design, experimentation, data analysis, interpretation of results, or preparation of the manuscript.

Authors' Contributions

Engr. Ojobo Marcus solely conceptualized the study, conducted biomass collection and preparation, performed torrefaction and pyrolysis experiments, analyzed the data, and prepared the full manuscript. No external collaborators contributed to this research.

Acknowledgements

The author expresses sincere appreciation to the **Tertiary** Education Trust Fund (TETFund) for providing financial support for this project through the IBR programme. Gratitude is also extended to the Management of Benue State Polytechnic, Ugbokolo, and the staff of the Department of Welding and Fabrication for their technical assistance, laboratory access, and institutional support throughout the research.

References

[1] A. A. Adeleke, I. S. Okafor, A. O. Ikubanni, P. O. Nzerem, S. S. Emmanuel, and G. O. Olatunde, "Characterization of selected Nigerian lignocellulosic biomass for solid biofuel production," *Energy Reports*, vol. 6, pp. 1052–1061, 2020.

[2] A. M. Yahya, "Comprehensive characterization of some selected biomass for bioenergy production," *BMC Bioenergy*, vol. 2, no. 1, pp. 1–16, 2023.

[3] M. D. Ibrahim, Y. A. Abakr, S. Gan, S. Thangalazhy-Gopakumar, and L. Y. Lee, “Intermediate pyrolysis of Bambara groundnut shell under inert atmospheres,” *Energies*, vol. 15, no. 22, 8421, 2022.

[4] J. Musa, I. Sada, A. Salisu, and A. Lawal, “Pyrolysis kinetics and energy content of acid-washed rice husk using isoconversional methods,” *FUDMA Journal of Sciences*, vol. 5, no. 3, pp. 237–246, 2021.

[5] F. E. Okoro, P. C. Okeke, and O. A. Charles, “Energy potential of palm kernel shell and its suitability for biofuel applications in Nigeria,” *Renewable Energy Focus*, vol. 36, pp. 98–105, 2021.

[6] J. T. Nwabanne, C. M. Onyelucheya, and S. A. Iwarere, “Thermogravimetric and elemental characterization of Nigerian groundnut shell,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1322, no. 1, 012003, 2024.

[7] A. Adewale G. Adeniyi, T. E. Odetoye, J. Titiloye, and J. O. Ighalo, “Thermodynamic study of rice husk pyrolysis,” *Eur. J. Sustainable Dev. Res.*, vol. 7, 2023.

[8] A. M. Umaru and I. A. Bawa, “Assessment of corncob as a solid biofuel: proximate, ultimate and calorific evaluation,” *J. Appl. Sci. Environ. Manage.*, vol. 24, no. 3, pp. 503–507, 2020.

[9] National Bureau of Statistics (NBS), *Annual Agricultural Performance Survey Report*, Abuja, Nigeria, 2022.

[10] Food and Agriculture Organization (FAO), *FAOSTAT Statistical Database*, Rome, Italy, 2023.

[11] M. M. Salleh et al., “Thermal degradation behaviour of biomass residues and implications for torrefaction,” *Renewable Energy*, vol. 168, pp. 1–12, 2021.

[12] R. Wu, Z. Zhang, and Y. Cai, “Effect of torrefaction temperature on physicochemical properties of biomass,” *Bioresource Technology*, vol. 346, 126618, 2022.

[13] D. Ciolkosz and R. Wallace, “A review of torrefaction for bioenergy feedstock production,” *Biofuels, Bioprod. Bioref.*, vol. 5, pp. 317–329, 2011.

[14] S. van der Stelt, H. Gerhauser, J. Kiel, and K. Ptasinski, “Biomass upgrading by torrefaction,” *Biomass Bioenergy*, vol. 35, no. 9, pp. 3748–3762, 2011.

[15] Y. Mei, Y. Zheng, H. Chai, and Y. Chen, “Effect of torrefaction on biomass pyrolysis: a thermogravimetric study,” *Energy Sources A*, vol. 46, pp. 6685–6695, 2024.

[16] A. A. Adeleke and A. O. Ikubanni, “Assessment of torrefied sawdust briquettes,” *Bioenergy Research*, vol. 14, pp. 543–553, 2021.

[17] O. A. Akogun and M. A. Waheed, “Fuel characteristics of biomass briquettes from cornhusk, cassava peels and sawdust,” *Biomass Convers. Bioref.*, vol. 13, pp. 3119–3129, 2023.

[18] C. Branca and C. Di Blasi, “Kinetics of biomass pyrolysis: revisiting the compensation effect,” *Fuel*, vol. 258, 116130, 2019.

[19] *No citation 19 appears in the manuscript.*

[20] T. Burnham, “Application of model-free kinetic methods to biomass pyrolysis,” *Thermochimica Acta*, vol. 689, 178–186, 2020.

[21] S. L. Wang et al., “Kinetic analysis of biomass torrefaction and pyrolysis using isoconversional methods,” *Energy*, vol. 237, 121612, 2021.

[22] X. Li, M. Zhang, and T. Bridgwater, “Torrefaction of lignocellulosic biomass and its impact on pyrolysis behaviour,” *Renewable Energy*, vol. 180, pp. 361–372, 2021.

[23] A. Ates, “Comparison of torrefied and raw biomass in fuel performance,” *Fuel Processing Technology*, vol. 224, 106994, 2021.

[24] X. Chen et al., “Upgrading biomass via torrefaction and its implications for energy conversion,” *Energy Conversion and Management*, vol. 273, 116350, 2023.

[25] N. U. Friday and J. O. A. Oboh, “Combustion and thermal decomposition characteristics of selected Nigerian agro-residues,” *Thermal Science and Engineering Progress*, vol. 25, 101095, 2021.

[26] M. A. Niziolek et al., “Physicochemical transformations of biomass during torrefaction,” *ACS Sustainable Chem. Eng.*, vol. 10, no. 5, pp. 2088–2098, 2022.

[27] F. Muhammad-Lawal, A. Omotesho, “Groundnut production constraints and opportunities in Nigeria,” *Nig. J. Agric. Econ.*, vol. 9, no. 1, 2021.

[28] K. O. Aremu et al., “Fuel properties of sawdust from Nigerian wood species,” *Energy Reports*, vol. 6, pp. 1052–1061, 2020.

[29] B. Mukherjee, “Thermal decomposition behavior of torrefied biomass,” *Journal of Analytical and Applied Pyrolysis*, vol. 161, 105336, 2021.

[30] D. O. Usino, P. Ylitervo and T. Richards, “Fast co-pyrolysis of palm kernel shell and sawdust,” *Molecules*, vol. 28, 6809, 2023.

[31] J. Lei et al., “Pyrolysis kinetics, mechanism and thermodynamics of peanut shell,” *Scientific Reports*, vol. 15, 2025.

[32] M. A. Gómez et al., “Improving energy yield through biomass torrefaction and co-firing,” *Energy Conversion and Management*, vol. 252, 115084, 2022.

[33] A. B. Kambal et al., “Co-firing torrefied biomass with coal for cleaner electricity generation,” *Process Safety and Environmental Protection*, vol. 158, pp. 62–75, 2022.

[34] N. Hanif et al., “Torrefaction for bioenergy: impact on grindability and fuel quality,” *Biomass & Bioenergy*, vol. 164, 106513, 2022.

[35] R. Shrestha and A. Kumar, “Techno-economic assessment of biomass torrefaction processes,” *Renewable and Sustainable Energy Reviews*, vol. 164, 112556, 2022.

[36] A. Musa et al., “Nigeria’s biomass energy resources and utilization pathway,” *Energy Policy*, vol. 169, 113216, 2023.

[37] N. Mohammed and M. I. Abubakar, “Thermal behaviour and TGA characterization of palm kernel shell,” *BioResources*, vol. 16, no. 4, pp. 7450–7465, 2021.