



Research article

Integrated feedstock chemistry and prepared-microstructure controls on inert decomposition of briquetted biomass residues: Groundnut shell versus pine wood chippings

Onep Samuel George^a, Obinna Onyebuchi Barah^{a,*}, Stephen Ndubuisi Nnamchi^b,
Milon Selvam Dennison^a

^a Department of Mechanical Engineering, School of Engineering and Applied Sciences, Kampala International University, P.O. Box 20,000, Kampala, Uganda

^b Department of Mechanical and Industrial Engineering, FAST, Mbarara University of Science and Technology, P.O. Box 1410, Mbarara, Uganda

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ABSTRACT

Feedstock variability remains a major constraint in small-scale biomass conversion systems, yet preliminary feedstock screening often relies on bulk fuel properties that provide limited insight into decomposition behavior. This study compares binder-less briquetted groundnut shell (GNS) and pine wood chippings (PWC) to determine how bulk composition, prepared-surface morphology, surface elemental signals, and broad functional-group signatures coincide with inert thermal decomposition behavior. Both feedstocks were conditioned to low moisture content and characterized using proximate analysis, higher heating value determination, thermogravimetric analysis under nitrogen, SEM-EDX, and ATR-FTIR. PWC exhibited higher volatile matter than GNS (71.88 vs. 67.40 wt% db.) and lower ash content (1.72 vs. 3.30 wt% db.), whereas GNS showed higher fixed carbon (19.94 vs. 17.18 wt% db.) and higher HHV (18.87 vs. 17.04 MJ kg⁻¹). Under inert heating, PWC decomposed earlier, with lower onset and peak decomposition temperatures, whereas GNS retained substantially more terminal residue at 1000 °C. SEM revealed a more heterogeneous, fracture-dominated prepared surface for GNS and a more fibrous, channel-like prepared surface for PWC. EDX and ATR-FTIR further supported differences in detected surface elemental balance and broad functional-group profiles. Overall, the results demonstrate statistically consistent differences between the two briquetted residues and establish a characterization-based basis for cautious preliminary screening. In the absence of ultimate analysis, direct lignocellulosic fractionation, mineralogical analysis, and reactor-scale gasification testing, the findings define a comparative laboratory basis for interpreting inert decomposition behavior, rather than a predictive framework for gasifier performance.

1. Introduction

Downdraft biomass gasifiers remain attractive for decentralized heat and power generation because their sequential drying, pyrolysis, oxidation, and reduction zones can support relatively low-tar producer gas compared with several other fixed-bed configurations [1,2]. In practice, however, stable operation is still strongly constrained by feedstock variability. Persistent tar formation, unstable thermal profiles, irregular bed behavior, and choking are frequently reported when reactor operation is transferred across biomass types that differ in physical structure and chemical composition [2,3]. Even when moisture content, particle size, and heating value fall within acceptable ranges, field and pilot-scale studies show that nominally similar fuels can still

produce markedly different gas quality, residue behavior, and pressure-drop evolution under comparable operating conditions [4]. For small-scale systems, this variability reduces fuel flexibility, complicates operating control, and narrows the practical operating window [5,6].

Conventional feedstock assessment for gasification is still dominated by bulk descriptors such as proximate analysis, ultimate analysis, ash content, and higher heating value. These parameters are necessary for mass and energy balance considerations, but they do not fully explain why different biomasses can exhibit different thermal decomposition pathways, residue persistence, and apparent conversion behavior under otherwise similar heating conditions [1,7,8].

More detailed studies sometimes include lignocellulosic composition or total alkali content, yet these are often treated as isolated descriptors

* Corresponding author.

E-mail address: obinna.barah@kiu.ac.ug (O.O. Barah).

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rather than as part of a broader structure–chemistry picture influencing volatile release, solid-phase transformation, and ash-related behavior during thermochemical conversion [9–12]. As a result, much of the literature remains descriptive at the feedstock-screening stage, especially when attempting to relate physicochemical differences to decomposition behavior relevant to subsequent gasification.

A further limitation is that feedstock morphology, surface-resolved inorganic chemistry, and functional-group signatures are often reported separately rather than interpreted together. Yet these characteristics may reasonably shape how a biomass responds during heating. Microstructural features such as fibrous channels, fracture networks, or compacted surfaces can influence local heat penetration and volatile escape. Inorganic species, particularly alkali and alkaline earth metals, may affect thermal transformation pathways, although their role depends not only on abundance but also on distribution and accessibility [13–15].

Likewise, oxygen-containing functional groups reflect differences in biomass chemistry that may be associated with differences in decomposition onset and residue formation during heating [16,17]. For comparative feedstock evaluation, the unresolved issue is therefore not whether these features exist, but how far they can be organized into a useful screening perspective alongside standard bulk properties.

Against this background, a practical gap remains in characterization-based studies aimed at biomass conversion: many provide standard bulk fuel data, but fewer examine how thermal decomposition profiles under controlled inert heating compare with microstructural and surface-chemistry observations in a way that is useful for cautious feedstock screening. This gap is particularly relevant where reactor-scale testing is costly or unavailable, and where preliminary selection of biomass candidates must rely on laboratory characterization. At the same time, such screening must be framed carefully. Inert thermogravimetric analysis does not reproduce the full reactive complexity of downdraft gasification, including oxidation, gas–solid reactions, tar cracking, or axial temperature gradients. Therefore, characterization results should not be treated as direct predictors of reactor performance, but they can still provide a structured basis for comparing feedstocks before more advanced conversion testing.

The choice of GNS and PWC is also relevant to residue availability in Uganda. Groundnut production generates substantial shell residues after processing, and national agricultural statistics have reported large quantities of unshelled groundnuts, with shell fractions contributing a significant waste stream after milling. In the Ugandan context, such residues are often underutilized, accumulated around processing sites, or disposed of through low-value pathways. Wood-processing residues, including pine chippings, are similarly generated from timber conversion and sawmill operations. These agricultural and woody residues therefore represent locally available biomass streams whose comparative characterization can support more systematic residue valorization and preliminary feedstock selection for decentralized thermochemical conversion.

Accordingly, this study compares groundnut shell (GNS) and pine wood chippings (PWC) using proximate analysis, higher heating value determination, thermogravimetric analysis under inert atmosphere, scanning electron microscopy, surface-resolved energy-dispersive X-ray spectroscopy, and ATR-FTIR. The aim is not to propose a predictive model of downdraft gasifier behavior, but to examine whether differences in bulk composition, surface morphology, inorganic surface signals, and functional-group envelopes are reflected in differences in inert thermal decomposition behavior. In this sense, the study addresses a narrower but useful question: how far can common laboratory characterization methods, when interpreted together, support a comparative screening perspective for biomass feedstocks?

The contribution of this work lies in a statistically supported, multi-technique integration that brings thermal, morphological, and spectroscopic observations into a consistent comparative framework for feedstock screening. Rather than treating these measurements as separate

results, the study evaluates them together to identify consistent differences between an agricultural residue and a woody biomass. The novelty does not lie in the individual methods, which are well established, but in how their combined interpretation reveals differences in devolatilization onset, mass-loss progression, and terminal residue under inert heating. In this form, the study provides a characterization-based, hypothesis-generating basis for feedstock comparison that can guide subsequent reactor-scale investigation, without extending the results to direct predictions of tar formation, gas quality, or reactor stability.

2. Materials and methods

2.1. Feedstock conditioning

Groundnut shells (GNS) and pine wood chippings (PWC) were sourced as agro-waste materials from two locations in Uganda and selected as representative agricultural-residue and woody-biomass feedstocks for comparative characterization. The GNS samples were obtained from local farmer groups in Kumi Municipality, Eastern Uganda, located at approximately 1.486° N latitude and 33.935° E longitude. The PWC samples were obtained from Kizinda Trading Centre, Bushenyi District, Western Uganda, located at approximately 0°32'58" S latitude and 30°06'56" E longitude, corresponding to decimal coordinates of −0.54969° latitude and 30.11560° longitude.

Prior to analysis, both materials were conditioned to reduce extrinsic variability associated with moisture content, particle-size heterogeneity, and visible contamination. The feedstocks were sun-dried for approximately 76 h until the measured moisture content was below 12 wt% on an as-received basis. Visible foreign materials, including metallic fragments and soil-derived impurities, were removed manually. The dried materials were then size-conditioned and densified by binder-less briquetting using a hydraulic biomass briquette press machine (type BPH 3/70, No. A0402, 03/2011) operated at 80 MPa to produce cylindrical briquettes of uniform geometry. The briquetted samples were sealed in airtight polyethylene bags and stored under ambient laboratory conditions prior to characterization to minimize moisture re-adsorption.

2.2. Proximate analysis

Moisture content, volatile matter, ash, and fixed carbon were determined following procedures [18]. Moisture content was reported on an as-received basis, whereas volatile matter, ash, and fixed carbon were reported on a dry basis. Moisture and volatile matter were obtained from measured mass losses, ash was determined after completion of the ashing step, and fixed carbon was calculated by difference.

All reported values are presented as mean $\pm$ standard deviation from three replicate determinations. For fixed carbon, uncertainty was propagated from the measured uncertainties associated with moisture, volatile matter, and ash.

2.3. Higher heating value

Higher heating value (HHV) was determined using a bomb calorimeter in accordance with ASTM D5865. For each determination, a known mass of sample was combusted in an oxygen-charged calorimetric vessel, and HHV was calculated from the measured temperature rise using the calibration and correction procedures specified by the standard.

All HHV measurements were carried out in triplicate for each feedstock, and results are reported as mean $\pm$ standard deviation.

2.4. Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed using an Eltra Thermostep analyzer in accordance with ASTM D7582. Approximately 5 mg of sample was heated from ambient temperature to 1000 °C at a

constant heating rate of 10 °C min⁻¹ under nitrogen. TG and DTG responses were recorded and used for comparative assessment of inert thermal decomposition behavior.

For the purposes of this study, T_{onset} was taken as the temperature at which the TG curve departed from the initial baseline and entered the main devolatilization region, T_{peak} as the temperature corresponding to the maximum mass-loss rate on the DTG curve, and residue as the normalized mass remaining at 1000 °C. These quantities were used as comparative descriptors of decomposition onset, peak devolatilization behavior, and terminal solid persistence under inert heating.

To improve reproducibility of the thermogravimetric descriptors, T_{onset} and T_{peak} were defined using standard analytical criteria derived from TG–DTG curves.

Onset temperature (T_{onset}) was determined using the tangent-intersection method, defined as the temperature at which the extrapolated tangent at the point of maximum slope of the TG curve intersects the initial mass baseline:

$T_{\text{onset}} = T_{\text{at intersection of baseline and tangent at max slope of TG curve}}$

where the baseline corresponds to the initial mass plateau prior to devolatilization.

Peak decomposition temperature (T_{peak}) was defined as the temperature corresponding to the maximum mass-loss rate, obtained from the DTG curve Eq. (1):

$$T_{\text{peak}} = \arg \max \left(-\frac{dW}{dT} \right) \quad (1)$$

where W is the sample mass and $\frac{dW}{dT}$ represents the rate of mass loss with respect to temperature.

These definitions were applied consistently across replicate runs to ensure comparability between feedstocks. All TGA measurements were performed in triplicate. The resulting parameters were used only for comparative interpretation of feedstock behavior under controlled inert heating and not as direct predictors of performance under reactive downdraft gasification conditions.

2.5. Scanning electron microscopy

Surface morphology was examined using a Zeiss Gemini 1 scanning electron microscope. For SEM observation, representative portions of the feedstocks were prepared as finely divided material and mounted on carbon tape, then coated with a 1–2 nm chromium layer to improve conductivity. Imaging was conducted under high vacuum at two representative spatial scales (nominal fields of view 20 µm and approximately 4 µm). Instrument settings, including accelerating voltage, working distance, detector mode, and magnification, are reported in the corresponding figure captions.

Because densification can alter native pore structure, the SEM observations are interpreted in this study as comparative surface-morphology observations of the prepared briquetted samples rather than as direct measurements of intact native pore architecture. The observed cavities, fractured domains, compact regions, grooves, and channel-like features may therefore reflect a combination of inherent biomass structure, size reduction, mounting/preparation effects, and high-pressure binder-less densification at 80 MPa. Accordingly, SEM-based descriptors are used only to compare the surface condition of the analyzed briquetted materials and are not treated as quantitative evidence of native porosity, permeability, or intrinsic pore accessibility.

2.6. Energy-dispersive X-ray spectroscopy

Elemental surface composition was examined by energy-dispersive X-ray spectroscopy (EDX) on SEM-observed fields. Both weight percent and atomic percent were recorded for the principal detected

elements, including C and O, together with minor inorganic elements such as Na, Mg, Si, P, Cl, K, and Ca where present.

Given the localized, surface-sensitive, and semi-quantitative nature of EDX, these results were used only for comparative assessment between the two feedstocks and not as absolute measures of bulk inorganic composition or mineral speciation. Quantification was based on standardless matrix correction, and the reported values correspond to area-averaged spectra unless otherwise stated.

2.7. Fourier-transform infrared spectroscopy

Fourier-transform infrared spectroscopy was performed in attenuated total reflectance mode using a Bruker Alpha II FTIR spectrometer equipped with a diamond ATR crystal. Prior to analysis, GNS and PWC samples were finely divided and gently homogenized to improve contact uniformity with the ATR surface. Before each measurement, the ATR crystal was cleaned, and a fresh background spectrum was collected under the same instrumental conditions. Each sample was placed directly on the diamond crystal and pressed uniformly against the crystal surface using the instrument pressure clamp to improve sample-crystal contact and minimize baseline instability.

Spectra were acquired over the mid-infrared region from 4000 to 400 cm⁻¹ at a spectral resolution of 4 cm⁻¹, using 32 co-added scans per sample. Replicate spectra were inspected for consistency before representative spectra were selected for comparative presentation. Baseline correction was applied before interpretation, and light smoothing was used only for visual presentation without altering peak positions or introducing artificial bands. No peak deconvolution, quantitative band fitting, or chemometric modelling was performed. Therefore, the ATR-FTIR data were used only to identify broad functional-group regions and to support qualitative comparison of functional-group signatures between GNS and PWC.

2.8. Derived indices for relative inorganic comparison

Where EDX elemental data were converted to oxide-equivalent form for comparative interpretation, simple inorganic indices were calculated using only the elements detected in the analyzed surface regions. In particular, an alkali/alkaline-earth metal fraction (AAEM fraction) was calculated as shown in Eq. (2):

$$f_{\text{AAEM}} = \frac{(K + Na + Ca + Mg)}{(K + Na + Ca + Mg + Si + P + Cl)} \quad (2)$$

Where applied, the base-to-acid ratio (B/A) was also estimated from the detected inorganic components for relative comparison only. Because these indices were derived from surface-resolved EDX data, they are inherently limited by the localized, semi-quantitative nature of the measurement and do not represent bulk ash chemistry, mineral speciation, or validated deposition behavior. Accordingly, they are used in this study only as comparative descriptors of the detected surface inorganic balance between GNS and PWC.

Overall, the analytical methods employed in this study were used to compare proximate composition, calorific value, inert thermal decomposition behavior, surface morphology, surface-resolved elemental signals, and FTIR spectral features across the two feedstocks [9,18,19]. These analyses are intended to support comparative characterization and hypothesis generation under controlled inert-heating conditions. They are not intended to predict absolute tar yields, slagging thresholds, or downdraft gasifier performance, and they do not substitute for reactor-scale testing under reactive conversion conditions.

2.9. Statistical analysis

All quantitative measurements, including proximate composition and higher heating value, were performed in triplicate and are reported

as mean $\pm$ standard deviation. To evaluate the statistical significance of differences between groundnut shell (GNS) and pine wood chippings (PWC), independent two-sample *t*-tests were conducted assuming unequal variances.

Statistical significance was assessed at a 95% confidence level ($p < 0.05$) for proximate composition and higher heating value measurements. Thermogravimetric descriptors, including T_{onset} , T_{peak} , T_{end} , maximum DTG rate, principal mass-loss reduction, and terminal residue, were extracted from TG-DTG profiles and used as curve-derived comparative indicators of inert decomposition behavior. Because SEM observations, EDX measurements, and FTIR spectra are inherently qualitative or semi-quantitative in this study, no formal statistical tests were applied to these datasets. Instead, consistency across multiple observations and spectral features was used as a basis for comparative interpretation. All statistical analyses were performed using standard spreadsheet-based calculations.

To improve methodological transparency, all quantitative measurements were performed in triplicate unless otherwise stated. Mean values and standard deviations are reported for proximate composition and HHV, while TG/DTG descriptors were extracted consistently from replicate thermal profiles. SEM, EDX, and ATR-FTIR were interpreted qualitatively or semi-quantitatively because they were used to support comparative characterization rather than formal statistical inference. This distinction was maintained throughout the interpretation to avoid overextending the dataset.

3. Results and discussion

3.1. Feedstock conditioning outcome

After conditioning, both GNS and PWC achieved moisture contents below 10 wt% on an as-received basis, providing a consistent basis for comparative characterization. Conditioning is therefore treated as a sample-standardization step rather than as an independent performance result.

3.1.1. Proximate composition and higher heating value of GNS and PWC

The measured bulk fuel properties of GNS and PWC are summarized in Table 1. Both feedstocks had similar conditioned moisture contents below 10 wt% (as received), but clear differences were observed in dry-basis composition and heating value. PWC exhibited a higher volatile matter content (71.88 wt% db.) and lower ash (1.72 wt% db.) and fixed carbon (17.18 wt% db.) than GNS, whereas GNS showed lower volatile matter (67.40 wt% db.), higher ash (3.30 wt% db.), higher fixed carbon (19.94 wt% db.), and a higher HHV (18.87 vs. 17.04 MJ kg⁻¹).

To assess the robustness of the observed differences, independent-sample *t*-tests were performed on replicate measurements. Differences in volatile matter, fixed carbon, ash content, and higher heating value between GNS and PWC were found to be statistically significant at the 95% confidence level ($p < 0.05$).

These results indicate that PWC is compositionally more volatile-rich, while GNS retains a comparatively larger non-volatile and inorganic fraction. Within the scope of this study, these contrasts provide an initial basis for interpreting later differences in inert thermal decomposition and terminal residue formation. However, because ultimate analysis and lignocellulosic fractionation were not performed, these

bulk properties are interpreted here only as comparative descriptors rather than as sufficient mechanistic explanations on their own.

Independent two-sample *t*-tests confirmed statistically significant differences in volatile matter, fixed carbon, ash content, and higher heating value between GNS and PWC ($p < 0.05$). Thermogravimetric descriptors, including T_{onset} , T_{peak} , T_{end} , maximum DTG rate, principal mass-loss reduction, and terminal residue, were extracted from the TG-DTG profiles and used as comparative indicators of inert decomposition behavior.

3.1.2. Thermogravimetric behavior under inert heating

The TG mass-loss curves of GNS and PWC under nitrogen are shown in Fig. 2, and the corresponding DTG profiles are shown in Fig. 3. Both feedstocks exhibited the expected general pattern of limited low-temperature mass loss, followed by a dominant devolatilization region and a progressively slower mass-change region at higher temperature. Despite this broadly similar overall behavior, the two feedstocks differed clearly in decomposition onset, peak decomposition temperature, and terminal residue.

PWC entered the principal devolatilization interval earlier than GNS, with T_{onset} of approximately 316 °C compared with approximately 348 °C for GNS. The maximum DTG-response temperature occurred at approximately 638 °C for PWC and 675 °C for GNS, while the principal decomposition interval extended to approximately 620 °C for PWC and 640 °C for GNS. The maximum DTG rate was approximately 0.793% min⁻¹ for PWC and 0.837% min⁻¹ for GNS. Across the principal decomposition interval, PWC showed greater mass-loss reduction than GNS, 65.78% versus 61.00%, respectively. These curve-derived descriptors indicate that PWC began major devolatilization earlier and underwent greater mass loss across the main decomposition interval, whereas GNS showed delayed decomposition and greater solid-phase persistence under inert heating. In addition, the PWC DTG peak was broader than that of GNS, indicating that mass loss was distributed over a wider temperature interval. Under the same inert heating conditions, these observations, supported by statistically significant differences in T_{onset} and T_{max} ($p < 0.05$), indicate that PWC decomposed earlier and more extensively in the principal devolatilization region, whereas GNS retained greater thermal resistance before reaching its dominant decomposition stage.

The thermogravimetric descriptors extracted from the TG-DTG profiles are summarized in Table 2. The principal decomposition region began at approximately 348 °C for GNS and 316 °C for PWC, indicating earlier sustained devolatilization in PWC. The main decomposition event extended to approximately 640 °C for GNS and 620 °C for PWC, while the maximum DTG rates were approximately 0.837% min⁻¹ and

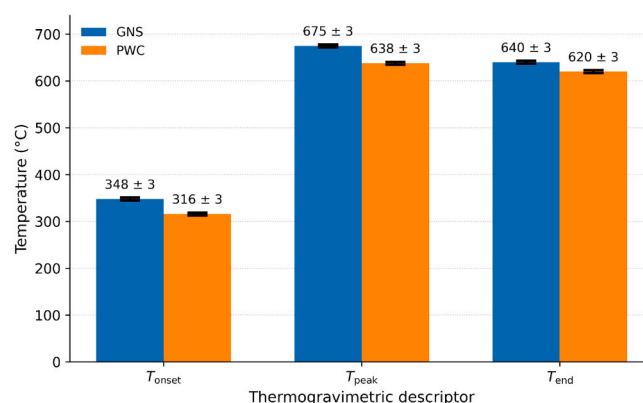


Fig. 1. Comparative thermogravimetric descriptors of groundnut shell (GNS) and pine wood chippings (PWC), including T_{onset} , T_{peak} , T_{end} , maximum DTG rate, principal mass-loss reduction, and terminal residue at 1000 °C. The values are presented as curve-derived comparative descriptors extracted from TG-DTG profiles under inert heating.

Table 1

Bulk fuel properties of GNS and PWC (mean $\pm$ SD; dry basis unless noted).

Property	GNS	PWC
Moisture (wt%, as received)	9.37 $\pm$ 0.30	9.23 $\pm$ 0.35
Volatile matter (wt%, db.)	67.40 $\pm$ 0.35	71.88 $\pm$ 0.40
Fixed carbon (wt%, db.)	19.94 $\pm$ 0.25	17.18 $\pm$ 0.30
Ash (wt%, db.)	3.30 $\pm$ 0.15	1.72 $\pm$ 0.10
HHV (MJ kg ⁻¹)	18.87 $\pm$ 0.20	17.04 $\pm$ 0.25

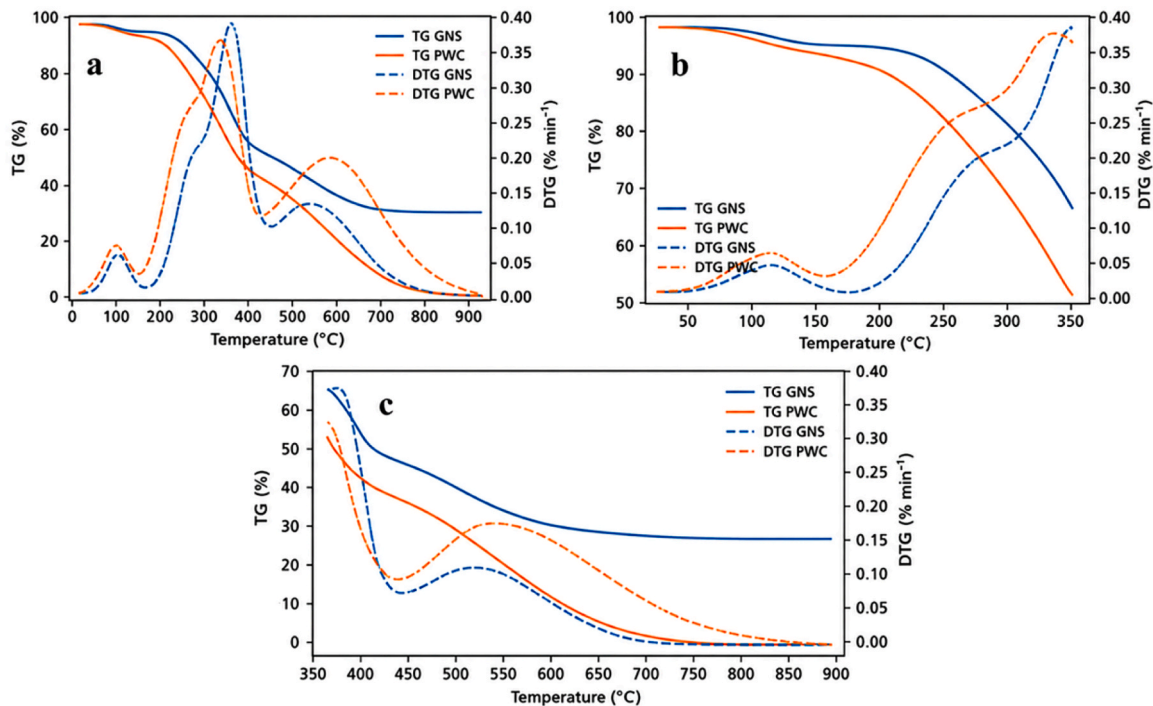


Fig. 2. Thermogravimetric and derivative thermogravimetric curves of groundnut shell (GNS) and pine wood chippings (PWC) under inert N₂ heating. Panel (a) shows the overall TG-DTG response, panel (b) highlights the low- to mid-temperature decomposition region, and panel (c) shows the high-temperature decomposition and residue-retention region. Solid lines represent TG mass remaining, while dashed lines represent DTG mass-loss rate.

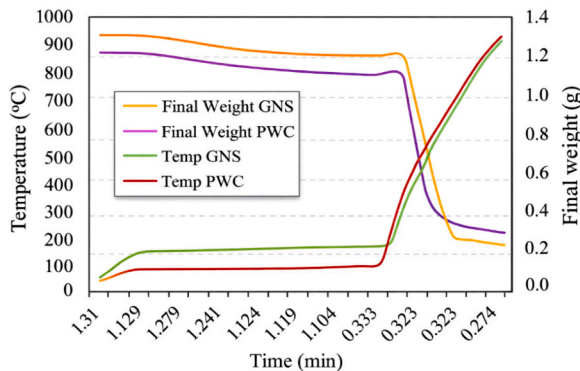


Fig. 3. Time-resolved temperature and final-weight profiles of groundnut shell (GNS) and pine wood chippings (PWC) during thermogravimetric heating. The temperature curves show the programmed heating progression toward 1000 °C, while the final-weight curves show the corresponding mass-retention behavior of the two feedstocks. GNS retained a larger final mass throughout the high-temperature stage, whereas PWC showed greater mass reduction, consistent with its higher volatile matter content and lower terminal residue.

0.793% min⁻¹ for GNS and PWC, respectively. These values indicate that PWC entered the main mass-loss region earlier, whereas GNS showed delayed decomposition and greater thermal persistence over the principal devolatilization interval.

These differences are further summarized in Fig. 1, where *T*_{onset}, *T*_{max}, and terminal residue are compared with associated variability, highlighting the consistent separation between the two feedstocks across replicate measurements.

The terminal residue at 1000 °C also differed markedly between the two feedstocks. GNS retained approximately 28 wt% residue, while PWC retained only about 3 wt%. This contrast is consistent with the higher fixed-carbon and ash fractions measured for GNS and the higher volatile matter measured for PWC. Within the limits of the present

Table 2
Thermogravimetric descriptors of GNS and PWC extracted from TG-DTG analysis under inert heating.

Parameter	GNS	PWC	Interpretation
<i>T</i> _{onset} (°C)	≈ 348	≈ 316	Start of the principal devolatilization interval
<i>T</i> _{peak} maximum DTG-response temperature (°C)	≈ 675	≈ 638	Temperature associated with maximum derivative mass-loss response
<i>T</i> _{end} (°C)	≈ 640	≈ 620	End of the principal decomposition interval
Maximum DTG rate (% min ⁻¹)	≈ 0.837	≈ 0.793	Maximum mass-loss intensity during the main decomposition event
Principal mass-loss reduction (%)	≈ 61.00	≈ 65.78	Extent of mass reduction across the principal decomposition interval
Terminal residue at 1000 °C (wt%)	≈ 28	≈ 3	Final solid persistence under inert heating

dataset, the TG-DTG results therefore support a comparative distinction between a more residue-persistent feedstock (GNS) and a more volatile-release-prone feedstock (PWC) under inert heating.

These findings are useful for comparing the two materials. The present TGA measurements were conducted under nitrogen and therefore do not reproduce the reactive conditions of downdraft gasification, such as oxidation, gas-solid reactions, tar cracking, or axial temperature gradients. Accordingly, the TG-DTG results are interpreted here as comparative indicators of inert thermal behavior rather than direct predictors of reactor-scale gasifier performance. Because cellulose, hemicellulose, lignin, and extractives were not directly quantified in this study, the observed differences in decomposition onset, peak decomposition temperature, and terminal residue are interpreted as comparative thermal descriptors rather than direct evidence of specific lignocellulosic fractions. Any reference to lignin-associated thermal persistence is therefore treated as a literature-grounded interpretation

that requires validation by direct lignocellulosic fractionation.

3.1.3. Surface morphology and surface-resolved elemental composition

SEM observations showed clear differences in the surface appearance of GNS and PWC at both examined scales (Figs. 4 and 5). At the 20 μm field of view, GNS appeared as a heterogeneous surface composed of fractured shell-like fragments, irregular cavities, and locally compact regions. In contrast, PWC displayed a more fibrous and lamellar organization, with elongated voids and more continuous channel-like features. At the finer scale (approximately 4 μm), GNS retained a mixed compact-fractured texture with fine cavities and microcracks, whereas PWC showed more distinct grooves and elongated void pathways associated with fibrous features.

In comparative terms, these observations indicate that the two feedstocks differ not only in bulk composition but also in their prepared surface morphology. PWC presented a more open and While these differences are visually consistent across multiple fields of view, they are interpreted as qualitative morphological distinctions rather than statistically quantifiable structural parameters. However, because the observations are based on prepared SEM samples and because densification may alter native pore structure, the images are interpreted here as comparative surface-morphology evidence rather than as direct quantitative measures of pore accessibility, permeability, or intact internal architecture. It is therefore important to distinguish prepared-surface morphology from native biomass architecture. The fracture-dominated appearance of GNS and the fibrous/channel-like appearance of PWC should not be interpreted as fully inherent pore structures of the original raw residues. Because both materials were size-conditioned and briquetted at 80 MPa before analysis, some observed features may have been introduced, compressed, exposed, or accentuated during densification and sample preparation. For this reason, the SEM evidence is used only to support within-study comparison of the analyzed briquetted samples, not to infer absolute pore accessibility or transport behavior.

The EDX spectra of both feedstocks (Figs. 6 and 7) were dominated by carbon and oxygen, with minor signals corresponding to Na, Mg, Si, P, Cl, K, and Ca. The reported surface-resolved quantifications indicate consistent trends across multiple analyzed, although no statistical inference is applied due to the localized and semi-quantitative nature of EDX measurements. The remaining inorganic elements were present at comparatively low levels in both feedstocks. Given the localized and semi-quantitative nature of EDX, these results are used only to describe relative differences in the detected surface elemental balance and should

not be interpreted as definitive evidence of bulk ash chemistry, mineral speciation, or catalytic behavior. In this study, they serve as supporting comparative indicators alongside the TG-DTG, SEM, and FTIR results.

3.1.4. ATR-FTIR functional-group signatures

The ATR-FTIR spectra of GNS and PWC are presented in Fig. 8, with detailed band assignments summarized in Tables 3 and 4. Both spectra exhibited broad absorption envelopes typical of lignocellulosic biomass, including O–H stretching bands, aliphatic C–H stretching bands, features in the double-bond region, and strong fingerprint-region bands. For GNS, the main annotated regions included O–H stretching at 3645–3600 cm^{-1} , C–H stretching at 2970–2950 and 2880–2860 cm^{-1} , $\text{C}\equiv\text{C}$ stretching at 2260–2190 cm^{-1} , C=N-related bands at 1690–1590 cm^{-1} , nitrate/nitro-related bands, and silicate-associated bands at 1100–900 cm^{-1} . For PWC, the main annotated regions included O–H stretching at 3570–3200 cm^{-1} , C–H stretching at 2935–2915 and 2880–2860 cm^{-1} , $\text{C}\equiv\text{C}$ -related bands at 2140–2100 and 2260–2190 cm^{-1} , C=C stretching at 1680–1620 cm^{-1} , N–H bending at 1650–1590 cm^{-1} , aromatic nitro bands, and silicate-associated bands at 1100–900 cm^{-1} . These assignments are used only to support qualitative comparison of broad functional-group signatures between the two feedstocks.

3.2. Discussion

The combined physicochemical characterization shows a consistent set of differences between GNS and PWC under the inert-heating conditions used in this study. Because both feedstocks were conditioned to similarly low moisture contents before analysis, the subsequent contrasts in TG-DTG behavior are less likely to arise from differences in initial drying demand and more likely to reflect differences in bulk composition and prepared material characteristics [20].

In this sense, conditioning improved comparability between the two feedstocks by reducing one important source of extrinsic variability. The proximate composition and HHV results provide the clearest first-level distinction between the materials. PWC contained more volatile matter and less ash and fixed carbon than GNS, whereas GNS exhibited the higher heating value. These contrasts are consistent with the observed inert thermal behavior. PWC decomposed earlier, reached its main DTG peak at a lower temperature, and underwent greater cumulative mass loss, while GNS showed delayed decomposition and retained substantially more terminal residue. Within the scope of the present

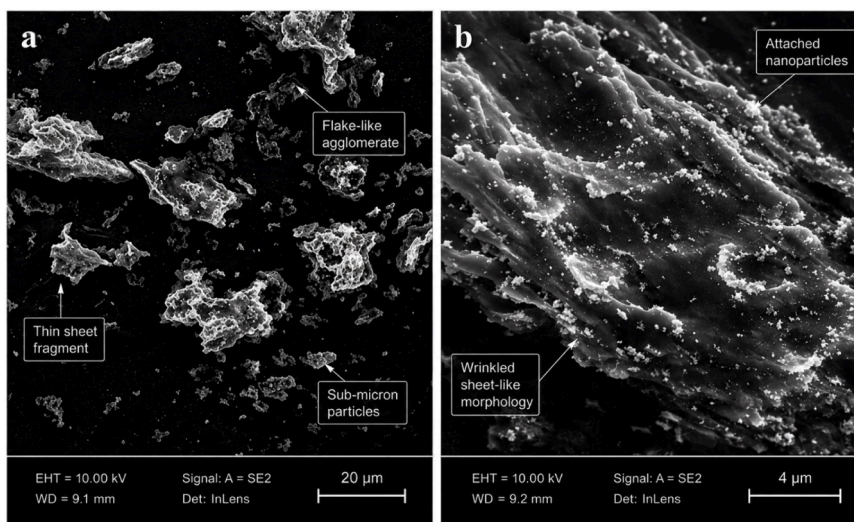


Fig. 4. SEM micrographs of groundnut shell (GNS) showing heterogeneous and fracture-dominated surface features at two observation scales. The prepared surface shows irregular cavities, fractured domains, and locally compact regions. These observations are presented as comparative first-order surface-morphology features only.

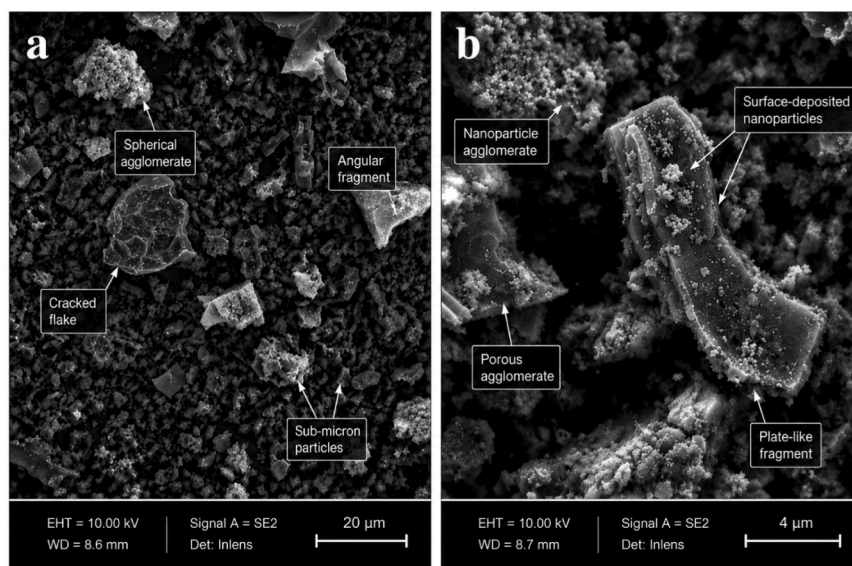


Fig. 5. SEM micrographs of pine wood chippings (PWC) showing fibrous and channel-like surface features at two observation scales. The prepared surface exhibits a more ordered fibrous structure with elongated grooves, interconnected voids, and channel-like features. These observations are presented as comparative first-order surface-morphology features only.

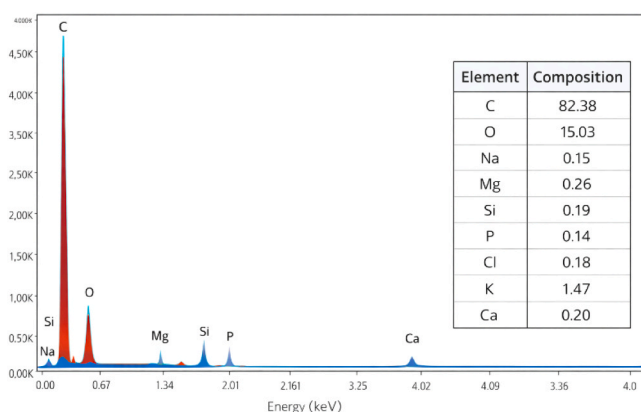


Fig. 6. Energy-dispersive X-ray spectroscopy (EDX) spectrum of groundnut shell (GNS). The spectrum is dominated by carbon and oxygen signals, with minor detected inorganic elements including K, Ca, Mg, Si, P, Na, and Cl. Insets highlight the low-energy region to aid relative comparison of detected surface elemental signals.

measurements, and supported by statistically significant differences in key parameters ($p < 0.05$), this pattern supports a comparative interpretation in which PWC behaves as the more volatile-release-prone feedstock under inert heating, whereas GNS shows greater solid-phase persistence [21]. However, because cellulose, hemicellulose, lignin, and extractives were not directly quantified by Van Soest, NREL, or equivalent lignocellulosic fractionation methods, the present study does not claim direct evidence of a higher lignin-rich fraction in GNS. Although cellulose, hemicellulose, and lignin contents were not directly measured in the present study, the observed differences can be interpreted using a literature-grounded lignocellulosic decomposition framework, in which hemicellulose typically contributes to earlier thermal decomposition, cellulose dominates the main devolatilization zone, and lignin decomposes over a broader and generally higher temperature range while contributing more strongly to char formation [22–24]. Within this constrained framework, the earlier decomposition of PWC is interpreted as being consistent with a more volatile-release-prone response, whereas the delayed decomposition and

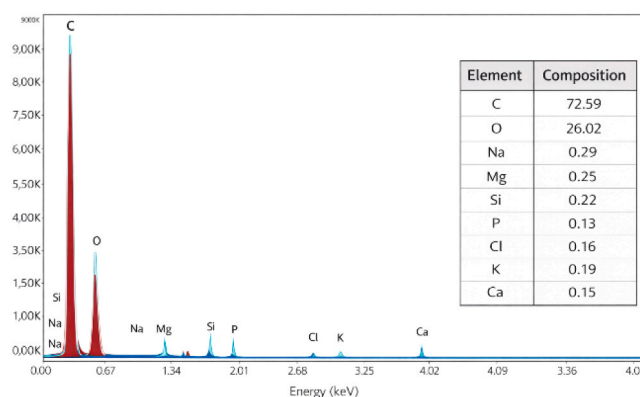


Fig. 7. Energy-dispersive X-ray spectroscopy (EDX) spectrum of pine wood chippings (PWC). Carbon and oxygen dominate the spectrum, while minor inorganic elements are detected at lower relative intensities. Insets show the low-energy region to support comparative assessment of detected surface elemental signals.

higher solid persistence of GNS are interpreted as being compatible with thermally persistent solid-forming constituents, including possible lignin-associated and ash-associated contributions. This interpretation is hypothesis-generating rather than direct compositional proof. At the same time, these bulk properties should not be treated as complete explanations of decomposition behavior, particularly because ultimate analysis and lignocellulosic fractionation were not performed in the present study.

The TG-DTG results also indicate that the distinction between the two feedstocks extends beyond the onset of devolatilization. Although both materials lost most of their mass in the intermediate-temperature decomposition region, GNS retained far more residue at 1000 °C than PWC. This observation is consistent with the higher fixed-carbon and ash contents measured for GNS and suggests greater terminal solid persistence under the inert conditions applied here. Conversely, the lower final residue of PWC is consistent with its higher volatile fraction and with more extensive mass loss over the heating program [9]. From the same literature-grounded perspective, the much higher terminal residue of GNS is also compatible with the broader thermal stability and

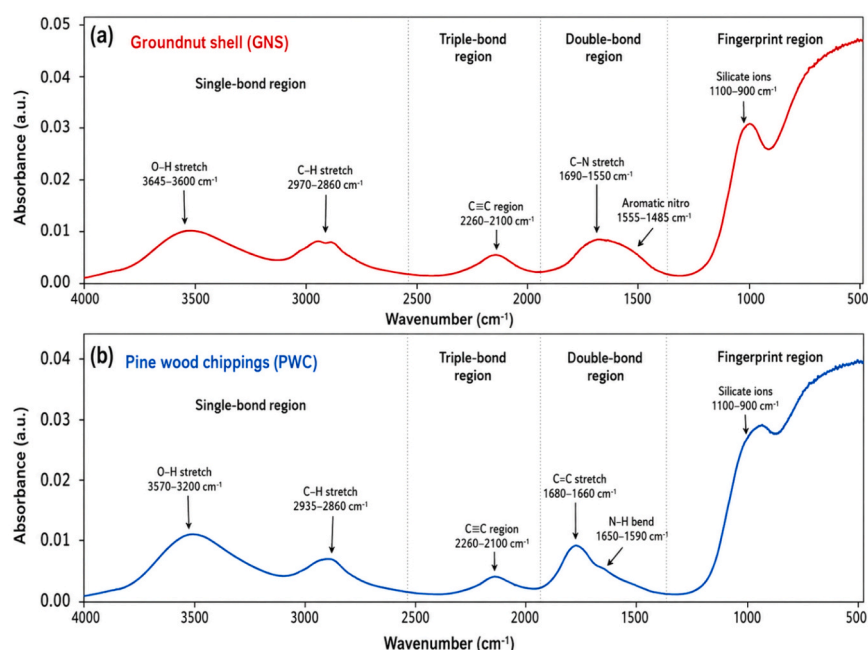


Fig. 8. ATR-FTIR spectra of briquetted biomass feedstocks: (a) groundnut shell (GNS) and (b) pine wood chippings (PWC). The spectra show broad absorption features typical of lignocellulosic biomass, including O–H stretching, aliphatic C–H stretching, unsaturated or heteroatom-containing bands in the double-bond region, and strong fingerprint-region features. Short annotations identify the principal bands used for comparative interpretation, while detailed band assignments are summarized in Tables 3 and 4. The spectra are interpreted qualitatively because no peak deconvolution, quantitative fitting, or independent lignocellulosic fractionation was performed.

Table 3

Functional groups identified in the GNS sample from ATR-FTIR analysis.

Bond region	Wavenumber range (cm ⁻¹)	Stretch/band position (cm ⁻¹)	Functional-group assignment
Single-bond region	2500–4000	2970–2950 / 2880–2860 / 3645–3600	Methyl C–H stretching Hydroxyl O–H stretching
Triple-bond region	2000–2500	2260–2190	Medial alkyne C≡C stretching
Double-bond region	1500–2000	1690–1590	Open-chain imino C=N stretching
		2000–1660	Aromatic combination bands
		1640–1620 / 1285–1270	Organic nitrate bands
		1555–1485 / 1355–1320	Aromatic nitro compound bands
Fingerprint region	600–1500	1100–900	Silicate ion-associated bands

stronger char-forming tendency generally associated with lignin-containing fractions, while the lower residue of PWC is consistent with more extensive devolatilization in the principal decomposition interval [23–25]. Importantly, this compatibility should not be read as direct evidence that GNS contains more lignin, because lignocellulosic fractionation was not performed. Rather, the higher terminal residue is directly supported by the measured fixed-carbon and ash contents, while the lignin-associated explanation remains a plausible literature-based interpretation requiring future validation. However, real-biomass pyrolysis behavior is not simply the linear sum of isolated cellulose, hemicellulose, and lignin responses, because interactions among these constituents can shift devolatilization behavior, apparent peak position, and char yield [22,25]. Accordingly, the present interpretation is best understood as a pseudo-mechanistic comparative framework rather than as direct compositional proof. These statistically supported observations provide a robust comparative basis for distinguishing the two feedstocks

Table 4

Functional groups identified in the PWC sample from ATR-FTIR analysis.

Bond region	Wavenumber range (cm ⁻¹)	Stretch/band position (cm ⁻¹)	Functional-group assignment
Single-bond region	2500–4000	2935–2915 / 2880–2860 / 3570–3200	Methyl C–H stretching Hydrogen-bonded hydroxyl O–H stretching
Triple-bond region	2000–2500	2140–2100 / 2260–2190	Terminal and medial alkyne C≡C stretching
Double-bond region	1500–2000	1680–1620	Alkenyl C=C stretching
		2000–1660	Aromatic combination bands
		1650–1590	Primary amine N–H bending
		1555–1485 / 1355–1320	Aromatic nitro compound bands
Fingerprint region	600–1500	1100–900	Silicate ion-associated bands

under inert heating conditions, but they should not be interpreted as direct evidence of behavior in reactive gasification environments, where oxidation, gas-solid reactions, and catalytic effects would also influence conversion.

The SEM observations provide additional comparative context. GNS showed a more heterogeneous and fracture-dominated prepared surface, with irregular cavities and compact domains, whereas PWC displayed a more fibrous structure with elongated grooves and channel-like voids. These differences may qualitatively align with differences in volatile-release behavior during inert heating, but they cannot be assigned solely to inherent native biomass architecture. Because both feedstocks were densified by binder-less briquetting at 80 MPa prior to analysis, the observed surface features may represent a combined outcome of original biomass anatomy, particle-size conditioning,

compression-induced deformation, fracture exposure, and sample mounting. In pseudo-mechanistic terms, a more open fibrous and channel-like prepared surface may be qualitatively consistent with easier volatile escape and a more distributed devolatilization interval, whereas more compact and fracture-dominated domains may be associated with greater local retention of solid material during heating. However, this interpretation is deliberately limited to the prepared briquetted samples and should not be read as evidence of intrinsic pore accessibility, native permeability, internal connectivity, or three-dimensional transport pathways. The SEM results are therefore best interpreted as first-order comparative morphology observations of the analyzed briquetted materials rather than direct evidence of pore-scale transport behavior [26]. However, the SEM images do not provide quantitative information on pore-size distribution, permeability, internal connectivity, or three-dimensional transport pathways. In addition, densification during briquetting may have modified native structural features.

The EDX results support a further comparative distinction between the feedstocks, although their interpretive scope remains limited. Both materials were dominated by carbon and oxygen, with minor detected inorganic signals including Na, Mg, Si, P, Cl, K, and Ca. GNS showed a relatively stronger potassium signal, whereas PWC showed a relatively higher oxygen signal. These observations indicate that the prepared surfaces of the two feedstocks differ in detected elemental balance, but they do not establish bulk inorganic composition, mineral form, or catalytic accessibility in a reactor environment. Accordingly, the higher surface-detected K in GNS may be relevant as a comparative indicator of surface chemical difference, but it should not be interpreted as direct evidence of catalytic activity or as a sufficient basis for explaining char persistence on its own [27].

Rather, within the present pseudo-mechanistic framework, the surface inorganic signals are treated only as supporting comparative descriptors that may accompany differences in thermal behavior, while remaining insufficient to establish catalytic causality without complementary bulk ash chemistry, mineralogical analysis, or reactivity testing.

The ATR-FTIR results further indicate that both feedstocks possess the broad functional-group envelope typical of lignocellulosic biomass, while differing in the relative prominence of selected bands. In the present study, these spectra are interpreted qualitatively rather than quantitatively. The broad O-H and aliphatic C-H regions confirm the expected lignocellulosic character of both feedstocks, while differences in band prominence across the mid-infrared and fingerprint regions suggest that the two materials are chemically similar in broad class but not identical in surface chemical signature. These differences are consistent with the observed contrasts in proximate composition and inert thermal decomposition behavior. In this respect, the FTIR results provide qualitative chemical-context support for the TG-DTG trends, because variations in broad functional-group prominence are at least compatible with differences in the relative contribution of lignocellulosic constituents known to influence biomass devolatilization behavior [22,23,25]. However, because no peak deconvolution, quantitative compositional fitting, or independent cellulose-hemicellulose-lignin analysis was performed, the FTIR results should be viewed only as supporting comparative evidence rather than as a basis for causal assignment of decomposition pathways [28]. Thus, ATR-FTIR is used here to support broad functional-group comparison only; it is not used to quantify lignin, cellulose, hemicellulose, extractives, or mineral phases, and it does not substitute for wet-chemical fractionation. The results support a cautious comparative interpretation: GNS and PWC differ not only in bulk fuel properties, but also in prepared surface morphology, detected surface elemental signals, and broad functional-group profile, and these differences coincide with distinct inert thermal decomposition patterns. In the present dataset, PWC is characterized by earlier devolatilization and lower terminal residue, whereas GNS shows delayed decomposition and greater solid persistence at high temperature [11,

17]. Collectively, these observations support a composition-informed, pseudo-mechanistic comparative framework in which bulk fuel properties define the first-order distinction, lignocellulosic decomposition theory provides a literature-grounded interpretive context rather than direct compositional evidence, prepared morphology offers qualitative context for volatile-release behavior, and surface inorganic signals provide limited supplementary evidence of chemical difference. The value of this multi-technique comparison lies in organizing these differences into a coherent characterization-based perspective for preliminary feedstock comparison. It does not establish a predictive or mechanistic framework for downdraft gasification, nor does it substitute for reactor-scale testing, quantitative pore analysis, mineralogical characterization, or compositional fractionation.

Although limited to two feedstocks, the statistically supported differences observed here provide a structured baseline for future expansion to larger datasets and validation under reactive gasification conditions. Future studies that include ultimate analysis, Van Soest, NREL, or equivalent cellulose-hemicellulose-lignin fractionation, and reactive conversion testing would allow the present pseudo-mechanistic interpretation to be tested more directly and refined into a broader comparative screening framework.

4. Exploratory within-study comparative synthesis

To organize the multi-technique characterization results into a transparent comparative summary, an exploratory within-study scorecard was developed using descriptors obtained directly from the present dataset, including proximate analysis and HHV, TG/DTG behavior, SEM observations, surface-resolved EDX results, and ATR-FTIR features. The scorecard is intended only as a qualitative synthesis of the GNS-PWC dataset and not as a statistically validated weighting model, universal ranking system, or predictive decision-support tool. Accordingly, it is presented as a visualization aid for summarizing how the two prepared briquetted feedstocks differ across the measured property domains, rather than as a transferable framework for feedstock selection or reactor-performance prediction.

Five descriptor groups were used to summarize broad differences in: (i) volatile-release tendency, (ii) solid-residue persistence, (iii) prepared-surface morphology, (iv) relative surface inorganic signal, and (v) ash burden. These descriptor groups were selected because they correspond directly to the main property domains examined experimentally in this study, namely proximate analysis/HHV, TG-DTG behavior, SEM observations, EDX results, and ATR-FTIR features. Each descriptor was assigned a 1–5 comparative score, where a higher score indicates a comparatively more favorable position within the GNS-PWC dataset only (Table 5). The score assignment was based on directional interpretation of the measured results within this dataset rather than on universal threshold values. For example, higher volatile matter together with earlier T_{onset} and lower T_{max} supported a higher comparative score for volatile-release tendency, whereas higher fixed carbon and greater terminal residue supported a higher comparative score for solid-residue persistence. Likewise, prepared-surface morphology was scored from qualitative SEM evidence of exposed grooves, apparent voids, fracture domains, and channel-like surface features in the analyzed briquetted samples. Because briquetting at 80 MPa can compress, expose, fracture, or otherwise modify native biomass structure, this descriptor was not treated as a measure of intrinsic pore accessibility or native morphology. It is included only as a within-study visual descriptor of the prepared sample surfaces.

The weighting scheme was introduced solely to structure the within-study comparison and is not statistically derived. The weights are interpreted as transparent interpretive coefficients and not optimized importance factors. They were not obtained from regression modelling, multivariate statistics, expert elicitation, sensitivity-validated decision analysis, reactor-scale validation, or a broader feedstock population. Importantly, the scorecard does not predict reactor performance, tar

Table 5
Illustrative comparative feedstock scorecard.

Descriptor group	Weight	GNS score	PWC score	Basis in this study
Volatile-release tendency	0.25	3	4	Volatile matter; TG/DTG onset and peak behavior; FTIR oxygenated/aliphatic band prominence
Solid-residue persistence	0.20	4	3	Fixed carbon; terminal TG residue; observed compact/fractured surface domains in SEM
Prepared-surface morphology	0.20	3	4	Qualitative SEM-observed prepared-surface features, including exposed grooves, apparent voids, fracture domains, and channel-like surface features after briquetting
Relative surface inorganic signal	0.20	4	2	Surface EDX K signal and AAEM fraction, where applied
Ash burden	0.15	3	4	Proximate ash content (dry basis); supporting qualitative FTIR mineral-related features

yield, slagging behavior, gasifier operability, or conversion efficiency, and it does not replace reactor-scale testing or validated process models. Because some descriptor groups, particularly those informed by SEM, EDX, and ATR-FTIR, retain qualitative or semi-quantitative components, the weighted index necessarily includes interpretive subjectivity. For this reason, the weighted index is reported as a dataset-specific qualitative synthesis and is not interpreted as a universal ranking of GNS, PWC, agricultural residues, woody biomass, or briquetted feedstocks more broadly.

As a robustness check, the original weighted index was examined against two alternative assumptions: equal weighting of all descriptor groups and one-factor-at-a-time $\pm 20\%$ perturbation of the assigned weights. The original weighting scheme produced closely similar indices for GNS and PWC, 3.45 and 3.35, respectively, whereas equal weighting gave an identical mean score of 3.40 for both feedstocks. The $\pm 20\%$ perturbation further indicated that the small separation between the two indices was sensitive to the selected weighting structure (Table 6). Accordingly, the scorecard are interpreted here as a dataset-specific qualitative synthesis rather than as evidence that either feedstock is universally superior. Its main value is to summarize contrasting property profiles: GNS is more strongly associated with solid-residue persistence and higher surface inorganic signals, whereas PWC is more strongly associated with volatile-release tendency, lower ash burden, and a more open prepared-surface appearance.

The descriptor scores should therefore be read only within the boundaries of the present two-feedstock comparison. A higher score for volatile-release tendency denotes comparatively earlier and more pronounced devolatilization under the inert-heating conditions used in this study, while a higher score for solid-residue persistence denotes greater retained solid fraction at high temperature. A higher score for prepared-surface morphology denotes a comparatively more open or channel-like appearance in the SEM fields of the analyzed briquetted samples. This descriptor does not represent intrinsic pore accessibility, native

Table 6
Sensitivity check for the exploratory weighted index.

Scenario	GNS index	PWC index	Interpretation
Original weighting	3.45	3.35	Slight GNS advantage, dataset-specific only
Equal weighting	3.40	3.40	No overall difference
$\pm 20\%$ one-factor perturbation	Weight-sensitive	Weight-sensitive	Ranking not robust enough for universal interpretation

permeability, or undisturbed biomass architecture, because binder-less briquetting at 80 MPa may have modified the original surface and pore structure.

Weighted comparative index ($\Sigma \text{ weight} \times \text{score}$):

- GNS: 3.45 / 5
- PWC: 3.35 / 5

The weighted comparative index has no standalone predictive meaning and is included only as a compact within-study summary of the relative scoring outcome. It should not be interpreted as a validated ranking metric beyond the present two-feedstock comparison.

Within the limits of the present dataset, the original weighting scheme gives a slightly higher index for GNS than for PWC (Fig. 9). However, the small difference between the two indices should not be interpreted as a robust ranking or evidence that GNS is generally superior to PWC. Instead, the scorecard indicates contrasting property profiles. GNS shows stronger indicators of solid-phase persistence, including higher fixed carbon and greater terminal residue under inert heating, together with a higher relative surface alkali signal in the EDX results. PWC, by contrast, scores higher in descriptors associated with earlier volatile release, lower ash burden, and a more open prepared-surface morphology. The equal-weight sensitivity check produced identical overall scores for the two feedstocks, further supporting the interpretation that the scorecard is best used as a qualitative visualization of trade-offs rather than as a definitive ranking metric. These differences are useful for comparative interpretation of the two materials, but they should not be generalized beyond the present measurements or treated as direct evidence of superior gasifier performance.

5. Limitations, future study, and Conclusion

5.1. Limitations

i. No direct reactor-performance or tar measurements:

The present work is based on laboratory characterization, including proximate analysis, higher heating value, TG/DTG, SEM-EDX, and ATR-FTIR. Accordingly, the results support comparative characterization and hypothesis generation rather than quantitative prediction of tar yield or speciation, syngas composition, pressure drop, gasifier operability, or conversion efficiency.

ii. Inert-atmosphere thermal analysis:

The thermal decomposition trends were obtained under nitrogen up to 1000 °C. Although these profiles are useful for relative comparison of decomposition onset, mass-loss progression, and terminal residue persistence, the reaction pathways and characteristic temperatures may differ under reactive gasification conditions involving air, steam, or CO₂.

iii. Surface sensitivity and semi-quantitative nature of EDX:

The EDX results represent localized surface-resolved elemental signals from selected fields and were obtained using standardless quantification [29]. They should therefore not be interpreted as measurements of bulk ash chemistry, mineral speciation, or direct evidence of catalytic behavior.

iv. Qualitative nature of FTIR interpretation:

The ATR-FTIR analysis was used to identify broad functional-group regions and relative differences in band prominence only [30]. Because no peak deconvolution, quantitative compositional fitting, or independent lignocellulosic fractionation was performed, the FTIR results should be regarded as supporting comparative evidence rather than definitive chemical assignment.

v. Limited feedstock set and effect of densification:

The present comparison includes only two feedstocks, one

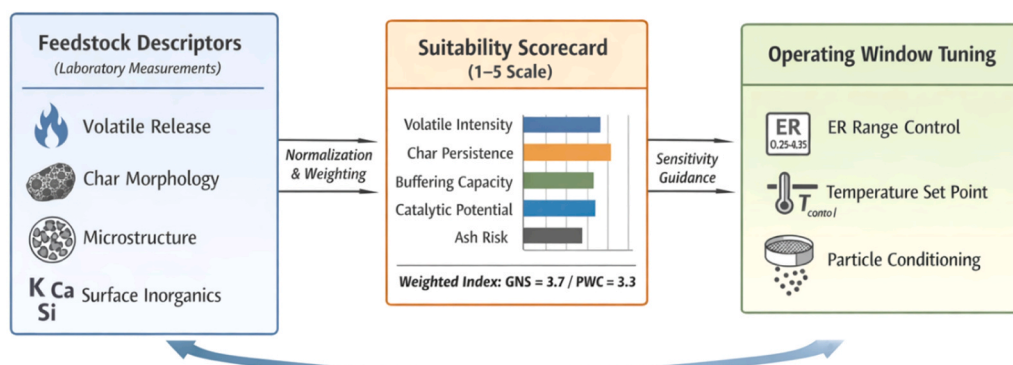


Fig. 9. Exploratory within-study comparative scorecard based on multi-technique characterization of GNS and PWC. The weighted index is a qualitative synthesis of this two-feedstock dataset only and is not a validated ranking tool or predictor of gasifier performance.

agricultural residue and one woody biomass, which limits generalization beyond the materials studied here. In addition, both feedstocks were binder-less briquetted at 80 MPa before analysis. This high-pressure densification may have compressed, fractured, exposed, or rearranged native pore structures and surface features. Therefore, the SEM observations and the prepared-surface morphology descriptor in the scorecard are treated as comparative features of the analyzed briquetted samples rather than as direct representations of intact raw biomass architecture, intrinsic pore accessibility, or native permeability.

5.2. Future study

To strengthen the present comparative characterization and extend it toward broader validation, future work should:

- (i) couple laboratory characterization with reactor-scale downdraft tests, including tar quantification and gas-composition analysis;
- (ii) perform reactive-atmosphere thermal analysis under CO₂, steam, or air to compare inert and reactive decomposition behavior;
- (iii) complement surface EDX with bulk ash chemistry and mineralogical characterization, for example by ICP-OES, XRF, or XRD; include ultimate analysis and lignocellulosic fractionation to improve interpretation of thermal and FTIR results; and
- (iv) examine the influence of particle form, including raw versus briquetted materials and different size classes, on morphology, flow behavior, and conversion response.

5.3. Conclusion

This study shows that groundnut shell (GNS) and pine wood chipings (PWC), despite comparable low moisture contents after conditioning, differ consistently across bulk fuel properties, inert thermal decomposition behavior, prepared surface morphology, detected surface elemental signals, and broad ATR-FTIR functional-group profiles. PWC exhibited higher volatile matter and earlier decomposition under nitrogen, together with lower terminal residue, whereas GNS showed higher fixed carbon, higher ash, higher-heating value, delayed decomposition behavior, and substantially greater residual mass at 1000 °C. The SEM observations indicated a more heterogeneous, fracture-dominated prepared surface for GNS and a more fibrous, channel-like surface for PWC, while EDX and ATR-FTIR provided supporting comparative evidence of differences in detected surface elemental balance and qualitative functional-group signatures.

Across these measurements, the statistically supported results provide a coherent comparative characterization-based interpretation of feedstock-dependent differences under inert heating conditions. More specifically, the results support a literature-grounded comparative interpretation in which measured differences in proximate composition,

prepared morphology, detected surface inorganic signals, and broad ATR-FTIR functional-group signatures coincide with distinct devolatilization and residue-retention behavior under inert heating. Because direct cellulose-hemicellulose-lignin fractionation was not performed, lignin-associated explanations are retained only as plausible hypotheses for future validation rather than as compositional conclusions. The value of the study lies in bringing together standard characterization methods to organize these differences into a coherent comparative perspective. The findings may help guide preliminary feedstock comparison and prioritization for subsequent conversion studies, but they do not constitute a predictive or validated framework for downdraft gasifier performance, tar behavior, or operational thresholds, and they do not replace reactor-scale testing.

Beyond its analytical contribution, the study also has practical relevance for biomass-resource utilization in settings where agricultural and woody residues are abundant but reactor-scale testing capacity is limited. By organizing standard characterization results into a structured comparative interpretation, the present work may support early-stage feedstock prioritization, reduce purely trial-and-error candidate selection, and contribute to more systematic biomass-residue valorization pathways. However, these environmental and economic implications remain indirect in the present work, because no direct reactor-performance, emissions, or techno-economic assessments were performed. Future studies combining broader feedstock datasets with reactive conversion testing, gasifier-performance measurements, and techno-economic evaluation are needed to validate and extend the comparative framework proposed here.

CRedit authorship contribution statement

Oney Samuel George: Conceptualization, Methodology, Investigation, Data curation, and Formal analysis. The doctoral thesis from which the manuscript was developed was based on his original research work.

Obinna Onyebuchi Barah: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, and Project administration. He was responsible for extracting, restructuring, synthesizing, and preparing the complete manuscript from the doctoral thesis from inception to finalization.

Stephen Ndubuisi Nnamchi: Methodology, Validation, Supervision, and Writing – review & editing. He supervised the doctoral research and provided scholarly and technical guidance.

Milon Selvam Dennison: Methodology, Validation, Supervision, and Writing – review & editing. He supervised the doctoral research and contributed scholarly and technical guidance.

All authors reviewed and approved the final version of the manuscript and agreed to be accountable for the accuracy and integrity of the work.

Declaration

The authors confirm that this manuscript is original and that they hold all legal rights to the intellectual property included. They also grant permission for the publication of this article.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The analyzed data are included within the article.

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