

Precursor-Dependent Effect of Urea Functionalization on CO₂ Capture by K₂CO₃-Activated Carbon Derived from Tembesu Wood and Bark

Idha Royani

idharoyani@unsri.ac.id

Universitas Sriwijaya

Widhi Mahatmanti

Universitas Negeri Semarang, Central Java

Silfiyana Fitria

Universitas Sriwijaya

Marathur Rodhiyah

Universitas Sriwijaya

Fiber Monado

Universitas Sriwijaya

Nilam Cahyati

Universitas Sriwijaya

Arika Suci Fitonna Ridassepri

Universitas Negeri Surabaya

Research Article

Keywords: Tembesu wood waste, activated carbon, K₂CO₃ activation, urea functionalization, CO₂ capture, biomass-derived carbon

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11085647/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Precursor-Dependent Effect of Urea Functionalization on CO₂ Capture by K₂CO₃-Activated Carbon Derived from Tembesu Wood and Bark

Idha Royani^{1,3*}, Widhi Mahatmanti², Silfiyana Fitria³, Marathur Rodhiyah¹, Fiber Monado¹, Nilam Cahyati¹, Arika Suci Fitonna Ridassepri⁴

¹Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Palembang, South Sumatera, 30139, Indonesia

²Departement of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Central Java, 50229, Indonesia

³Laboratory of Material Science, Faculty of Mathematics and Natural Science, Universitas Sriwijaya, Indralaya, South Sumatera, 30662, Indonesia

⁴Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Negeri Surabaya, East Java, 60231, Indonesia

*idharoyani@unsri.ac.id

ABSTRACT

This study aimed to investigate tembesu wood waste as a renewable precursor for CO₂-adsorbing activated carbon by comparing inner-wood and bark fractions and the responses to urea functionalization. The biomass fractions were converted into hydrochar through hydrothermal carbonization at 160 °C for 6 h, chemically activated with K₂CO₃ at 600 °C, and subsequently functionalized using urea. The materials obtained were characterized by thermogravimetric analysis (TGA), scanning electron microscopy coupled with ImageJ analysis, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and CO₂ temperature-programmed desorption (CO₂-TPD). The results showed that K₂CO₃ activation transformed the residual lignocellulosic structure into a predominantly disordered carbon framework and generated pronounced surface openings. Urea treatment produced precursor-dependent changes in surface chemistry, morphology, and oxidative thermal response. The mean apparent pore-opening diameters were 517 ± 160, 521 ± 189, 572 ± 159, and 615 ± 203 nm for KA-KT, KA-KT-N, KA-KKT, and KA-KKT-N, respectively. CO₂-TPD showed uptakes of 2.1844, 2.0966, 1.3835, and 2.1485 mmol g⁻¹, respectively. Urea functionalization slightly decreased CO₂ uptake of the inner-wood-derived carbon by approximately 4.0%, while it enhanced that of the bark-derived carbon by approximately 55.3%. These results demonstrate that urea functionalization is not universally beneficial but strongly depends on the physicochemical characteristics of the biomass precursor. Therefore, tembesu inner wood can provide effective CO₂ adsorbents through K₂CO₃ activation alone, while bark-derived carbon benefits substantially from subsequent urea functionalization.

Keywords: Tembesu wood waste; activated carbon; K₂CO₃ activation; urea functionalization; CO₂ capture; biomass-derived carbon

INTRODUCTION

The continuous increase in atmospheric carbon dioxide (CO₂) emissions associated with energy production, industrial activities, and transportation is a major contributor to global climate change. Therefore, the development of effective carbon capture technologies is essential for mitigating anthropogenic greenhouse gas emissions and supporting the transition toward a low-carbon energy system (1,2). Among the available carbon capture approaches, adsorption using porous solid materials has attracted considerable attention because of its relatively low energy requirement, operational flexibility, and potential for adsorbent regeneration. A variety of porous materials, including zeolites, mesoporous silica, and porous carbon, have been investigated for CO₂ capture (3,4). However, performance can be strongly influenced by surface chemistry, pore structure, and interaction with water under practical operating conditions (5–7). These considerations have stimulated increasing interest in the development of porous adsorbents with tunable textural properties and surface functionalities.

Porous carbon materials are particularly attractive for CO₂ capture because of their high chemical stability, adjustable pore structure, relatively low production cost, and compatibility with a wide range of carbonaceous precursors (8). The adsorption performance of porous carbon is determined by the interplay between its textural properties and surface chemistry. In particular, the development of narrow micropores can enhance the

confinement and physical adsorption of CO₂, while the incorporation of heteroatom-containing surface functionalities modifies the surface polarity and affinity toward acidic molecules. Therefore, nitrogen functionalization has been widely investigated as a strategy to tailor the surface chemistry of porous carbon and potentially improve CO₂ adsorption through interactions between nitrogen-containing functionalities and CO₂ (9, 10). The effect of nitrogen incorporation is not necessarily universal, as the introduction of nitrogen-containing species may also alter the pore structure, block or partially narrow existing micropores, and consequently affect the accessibility of adsorption sites. This suggests that the relationship between nitrogen functionalization, pore structure, surface chemistry, and CO₂ adsorption remains highly dependent on the carbon precursor and synthesis conditions.

The sustainability of porous carbon production is also an important consideration in the development of capture materials. Conventional activated carbon are commonly produced from fossil-derived or non-renewable carbonaceous resources, including coal and petroleum-based precursors, which may reduce the environmental benefits of their application in carbon capture (11,12). In contrast, lignocellulosic biomass represents an abundant and renewable carbon source that can be converted into value-added porous materials. Biomass residues generated from agricultural, forestry, and wood-processing activities are particularly attractive because their valorization can simultaneously address waste management and material production challenges (13,14,15). Therefore, converting the residues into porous carbon is consistent with the principles of circular economy and sustainable materials development.

Wood-processing waste is a particularly promising precursor because it contains cellulose, hemicellulose, and lignin, which experience complex structural transformations during hydrothermal carbonization and subsequent activation. The relative abundance of these components strongly influences carbon yield, aromaticity, pore development, surface functionality, and thermal stability. Consequently, biomass heterogeneity should not be considered only as a compositional characteristic but a potentially important factor controlling the final performance of biomass-derived carbon adsorbents. In particular, different anatomical fractions of wood may show substantially different lignocellulosic compositions and respond differently to carbonization, chemical activation, and surface functionalization.

Tembesu wood (*Fagraea fragrans* Roxb.) is a locally important hardwood species in Indonesia and is widely used in South Sumatra, particularly in furniture production (16,17). The processing generates substantial solid residues that remain underutilized despite their carbon-rich lignocellulosic composition. Therefore, valorizing the residues into functional carbon materials could provide both environmental and economic benefits while utilizing a locally available biomass resource. Importantly, tembesu biomass contains distinct anatomical fractions, including inner wood and bark, which may differ in the relative contents of cellulose, hemicellulose, lignin, and extractive compounds. These compositional differences are expected to influence hydrochar formation, K₂CO₃-assisted activation, pore development, surface chemistry, and the subsequent response of the resulting carbon to nitrogen functionalization.

Although biomass-derived porous carbon have been extensively investigated for CO₂ capture, the use of tembesu wood waste as a carbon precursor remains largely unexplored. More importantly, the influence of different tembesu biomass fractions on the structural evolution and CO₂ adsorption behavior of chemically activated and nitrogen-functionalized carbon has not been systematically elucidated. In particular, the relationship among precursor fraction, activation-induced structural development, nitrogen functionalization, and CO₂ adsorption performance remains insufficiently understood. Clarifying this relationship is important because an identical functionalization strategy may not necessarily produce the same physicochemical or adsorption response when applied to carbon materials derived from different anatomical fractions of the same biomass.

In this study, tembesu wood waste was separated into inner and bark fractions, which were then converted into porous carbon through hydrothermal carbonization, K₂CO₃ chemical activation, and subsequent urea-assisted nitrogen functionalization. The resulting materials were systematically characterized to evaluate changes in thermal behavior, surface morphology, functional groups, and structural organization, while their CO₂ adsorption behavior was assessed to determine the effects of biomass fraction and post-activation functionalization. Particular attention was given to the contrasting responses of inner-wood- and bark-derived activated carbon to urea treatment. The central hypothesis of this study is that the influence of nitrogen functionalization on CO₂ adsorption is strongly precursor-dependent and arises from the interplay among intrinsic biomass composition, activation-induced structural development, and changes in surface chemistry. Moreover, the novelty lies in showing that, within a single wood species, inner wood and bark have markedly different structural and CO₂-adsorption responses to the same K₂CO₃ activation and urea-functionalization routes. This implies that precursor fraction is

a critical design parameter rather than a passive biomass characteristic in the development of sustainable adsorbents.

EXPERIMENTAL SECTION

Material

Tembesu wood waste (*Fagraea fragrans* Roxb.) was collected from local small- and medium-scale furniture industries in the Ogan Ilir region of South Sumatra, Indonesia. The waste was separated into inner wood and bark fractions, then ground into powder before synthesis. Potassium carbonate (K_2CO_3) and urea ($CO(NH_2)_2$) were purchased from Sigma-Aldrich, while deionized and distilled water were used during the synthesis and washing procedures.

Before further processing, the biomass fractions were thoroughly cleaned to remove adhering impurities and dried to a constant mass. The dried material was mechanically ground and sieved to obtain a relatively uniform particle size. Unless otherwise stated, all chemicals were used without further purification.

Methods

Hydrothermal Carbonization

The inner-wood and bark fractions were separately subjected to hydrothermal carbonization (HTC). Each biomass fraction was mixed with distilled water at a solid-to-liquid ratio of 1:10 (w/v) and stirred until the biomass was completely wetted. The resulting suspension was then allowed to stand for 24 h to facilitate water penetration into the lignocellulosic matrix.

The biomass suspension was subsequently transferred into a hydrothermal autoclave and treated at 160 °C for 6 h. After hydrothermal treatment, the resulting hydrochar was recovered and thoroughly washed with distilled water until the washing solution reached neutral pH. The hydrochar was dried at 100 °C to constant mass. The same procedure was independently applied to the inner-wood and bark fractions. The resulting materials were designated HC-KT and HC-KKT, respectively.

K_2CO_3 Chemical Activation

The hydrochar obtained from the inner-wood and bark fractions was chemically activated using K_2CO_3 as the activating agent. Both materials were mixed at a mass ratio of 1:1 and dispersed in distilled water. The mixture was stirred at 60 °C for 2 h to promote intimate contact between the hydrochar and the activating agent.

The resulting suspension was subsequently dried and subjected to thermal activation at 600 °C for 1.5 h. After activation, the carbonized products were collected and washed with 3 M HCl to remove residual inorganic species and potassium-containing compounds formed during the activation process. The samples were repeatedly rinsed with deionized water until the washing solution reached neutral pH and subsequently dried at 100 °C to constant mass. The activated carbon derived from the inner-wood and bark fractions were designated KA-KT and KA-KKT, respectively.

Nitrogen Functionalization

Nitrogen functionalization of the activated carbon was carried out using urea as the nitrogen source. Each activated carbon sample was mixed with urea at a mass ratio of 1:1 and dispersed in 30 mL of ethanol. The mixture was stirred at 60 °C for 2 h and subsequently heated at 100 °C until a dry carbon–urea precursor was obtained.

The dried precursor was then subjected to hydrothermal treatment at 160 °C for 6 h. After treatment, the resulting carbon material was thoroughly washed with distilled water to remove residual soluble species and subsequently dried at 100 °C to constant mass. The nitrogen-functionalized activated carbon derived from the inner-wood and bark fractions were designated KA-KT-N and KA-KKT-N, respectively.

The dried precursor was then subjected to hydrothermal treatment at 160 °C for 6 h. After treatment, the resulting carbon material was thoroughly washed with distilled water to remove residual soluble species and subsequently dried at 100 °C to constant mass. The nitrogen-functionalized activated carbons derived from the inner-wood and

bark fractions were designated KA-KT-N and KA-KKT-N, respectively. The overall preparation route, including hydrothermal carbonization, K_2CO_3 activation, and subsequent urea functionalization, is schematically illustrated in Figure 1.

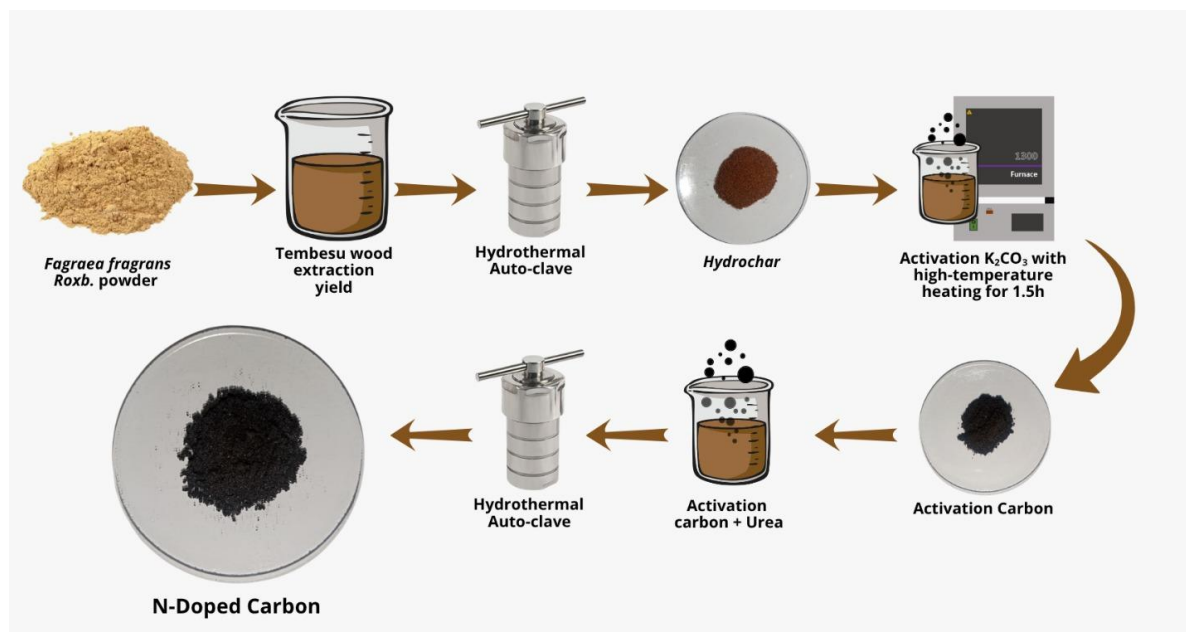


Figure 1. Schematic illustration of the preparation of tembesu-derived activated and nitrogen-functionalized carbons through hydrothermal carbonization, K_2CO_3 activation, and subsequent urea treatment.

Characterization

The physicochemical properties of the hydrochar, activated carbon, and nitrogen-functionalized carbon were investigated using complementary analytical techniques. Thermogravimetric analysis (TGA) was performed to evaluate the thermal decomposition and stability of the carbon materials as a function of temperature. The analysis was performed using a NETZSCH TG 209 F1 Libra thermogravimetric analyzer under an oxidative air atmosphere (Air, 80/20). Approximately 4.1–14.0 mg of each sample was placed in an open 85- μ L Al_2O_3 crucible. The temperature program consisted of heating from 20 to 100 $^{\circ}C$ at 20 $^{\circ}C$ min^{-1} , followed by an isothermal step at 100 $^{\circ}C$ for 30 min. The samples were subsequently heated from 100 to 800 $^{\circ}C$ at 50 $^{\circ}C$ min^{-1} and maintained at 800 $^{\circ}C$ for 30 min.

Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) was employed to examine surface morphology and elemental composition. Fourier-transform infrared spectroscopy (FTIR) was used to identify the major surface functional groups and monitor changes in the chemical structure following hydrothermal carbonization, K_2CO_3 activation, and nitrogen functionalization. X-ray diffraction (XRD) was conducted to evaluate the structural ordering and degree of crystallinity of the carbon materials.

The sample codes used throughout this study are summarized in Table 1.

Table 1. Sample designation and description

Sample	Description	Code
1	Inner-wood hydrochar	HC-KT
2	Bark hydrochar	HC-KKT
3	Inner-wood activated carbon	KA-KT
4	Bark activated carbon	KA-KKT
5	Nitrogen-functionalized inner-wood activated carbon	KA-KT-N
6	Nitrogen-functionalized bark activated carbon	KA-KKT-N

RESULTS AND DISCUSSION

3.1. Thermal Behavior

TGA was performed to evaluate the oxidative thermal behavior of activated and nitrogen-functionalized carbons derived from tembesu wood. As shown in Figure 2, all samples exhibited an initial low-temperature mass-loss stage followed by extensive mass loss during subsequent oxidative heating. Three samples approached a small positive residual fraction at the end of the experiment, whereas KA-KT-N exhibited a high-temperature baseline deviation that resulted in an apparent negative terminal mass. Under an oxidative atmosphere, the initial stage is mainly associated with the release of adsorbed moisture and weakly retained volatile species, whereas the subsequent mass loss involves decomposition of residual labile functionalities and, predominantly at elevated temperatures, oxidation of the carbonaceous framework (18,19). Similar oxidative behavior has been reported for biomass-derived carbon materials, in which the carbon matrix is extensively consumed at intermediate-to-high temperatures in air.

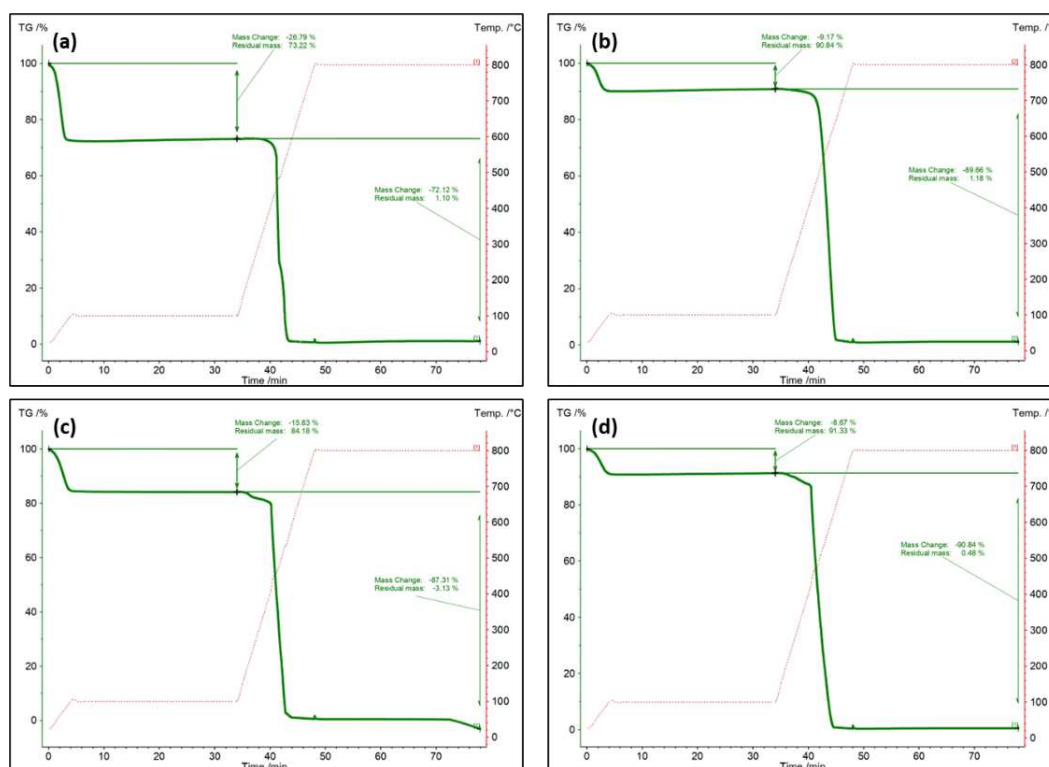


Figure 2. TGA profiles of tembesu-derived activated and nitrogen-functionalized carbons under oxidative conditions: (a) KA-KT, (b) KA-KKT, (c) KA-KT-N, and (d) KA-KKT-N

The low-temperature mass loss was determined during heating from 20 to 100 °C followed by a 30-min isothermal hold at 100 °C. KA-KT showed the highest mass loss in this stage (26.79%), while KA-KKT had a substantially lower value of 9.17%. After urea treatment, the corresponding values were 15.83% for KA-KT-N and 8.67% for KA-KKT-N. The relatively large mass loss of KA-KT indicates a greater combined content of adsorbed moisture and/or weakly retained volatile species compared to the bark-derived carbon. Low-temperature mass loss of biomass-derived activated carbon has similarly been attributed predominantly to adsorbed atmospheric moisture and residual volatile species. The magnitude of loss is affected by the physicochemical characteristics of the carbon surface (19).

The pronounced difference between KA-KT and KA-KKT further indicates that the thermal response was strongly dependent on the biomass fraction. Wood and bark contain different proportions and structural forms of cellulose, hemicellulose, lignin, extractives, tannins, and inorganic constituents. Consequently, these parts may experience different structural transformations during hydrothermal carbonization and chemical activation. A direct comparison of wood- and bark-derived hydrochar has demonstrated that precursor composition substantially affects the thermal characteristics and subsequent pore development of activated carbon (20). Moreover, the

reactivity of lignin- and tannin-derived carbon during K_2CO_3 activation depends strongly on their hydroxyl functionality, molecular structure, and inorganic content (21). This suggests that the contrasting mass-loss behavior of KA-KT and KA-KKT is more appropriately interpreted as a precursor-dependent response rather than solely a difference in intrinsic thermal stability.

Urea treatment particularly affected the low-temperature behavior of the inner-wood-derived carbon, decreasing the mass loss from 26.79% for KA-KT to 15.83% for KA-KT-N. In contrast, only a small difference was observed between KA-KKT (9.17%) and KA-KKT-N (8.67%). These results suggest that urea treatment altered the surface chemical environment and the retention of moisture and/or volatile species to different extents depending on the biomass precursor. Recent investigations of urea-modified activated carbon derived from different plant residues have similarly demonstrated that the effect of functionalization is strongly precursor-dependent and can modify surface chemistry, porosity, moisture affinity, and thermal response (22).

During the subsequent programmed stage, consisting of heating from 100 to 800 °C followed by a 30-min isothermal hold at 800 °C, extensive oxidative mass loss was observed for all samples. The reported losses were 72.12% for KA-KT, 89.66% for KA-KKT, 87.31% for KA-KT-N, and 90.84% for KA-KKT-N. These values represent the integrated mass loss over the entire second programmed stage and should not be assigned exclusively to a narrower temperature interval such as 300–500 °C. The large mass loss during this stage is mainly associated with oxidation and burn-off of the carbonaceous framework under the applied oxidative atmosphere. Oxidative TGA studies of biochar have shown that major carbon consumption occurs during the intermediate-to-high-temperature region and is strongly influenced by carbon structure and surface chemistry (18).

KA-KKT showed a greater second-stage mass loss than KA-KT, despite its substantially lower low-temperature mass loss. This indicates that lower moisture/volatile retention does not necessarily correspond to greater resistance of the carbon framework toward oxidation. Instead, the contrasting responses further support the important role of precursor chemistry in determining carbon reactivity. Guizani et al. demonstrated that structurally different lignin and tannin precursors show markedly different carbonization and K_2CO_3 -activation reactivities, suggesting the final thermal behavior of activated carbon cannot be separated from the chemistry of the original biomass (21).

The quantitative TGA characteristics are summarized in Table 2.

Table 2. Thermogravimetric characteristics of tembesu-derived activated and nitrogen-functionalized carbon under oxidative conditions.

Sample	Low-temperature mass loss* (%)	Subsequent mass loss** (%)	Final residue (%)
KA-KT	26.79	72.12	1.10
KA-KKT	9.17	89.66	1.18
KA-KT-N	15.83	87.31†	Not reliable†
KA-KKT-N	8.67	90.84	0.48

* Heating from 20 to 100 °C followed by a 30-min isothermal hold at 100 °C.

** Heating from 100 to 800 °C followed by a 30-min isothermal hold at 800 °C.

† The instrumental terminal value for KA-KT-N was −3.13%, indicating a high-temperature baseline/buoyancy-correction artifact. Consequently, its second-stage mass loss and final residue were not used for quantitative comparison.

The terminal value of −3.13% recorded for KA-KT-N is physically unrealistic and indicates a high-temperature baseline/buoyancy-correction artifact. Therefore, the corresponding second-stage mass loss was retained as the instrumental output but was excluded from quantitative comparison of oxidative thermal behavior. The low-temperature mass loss of KA-KT-N, which occurred before the baseline deviation became apparent, was retained for qualitative comparison.

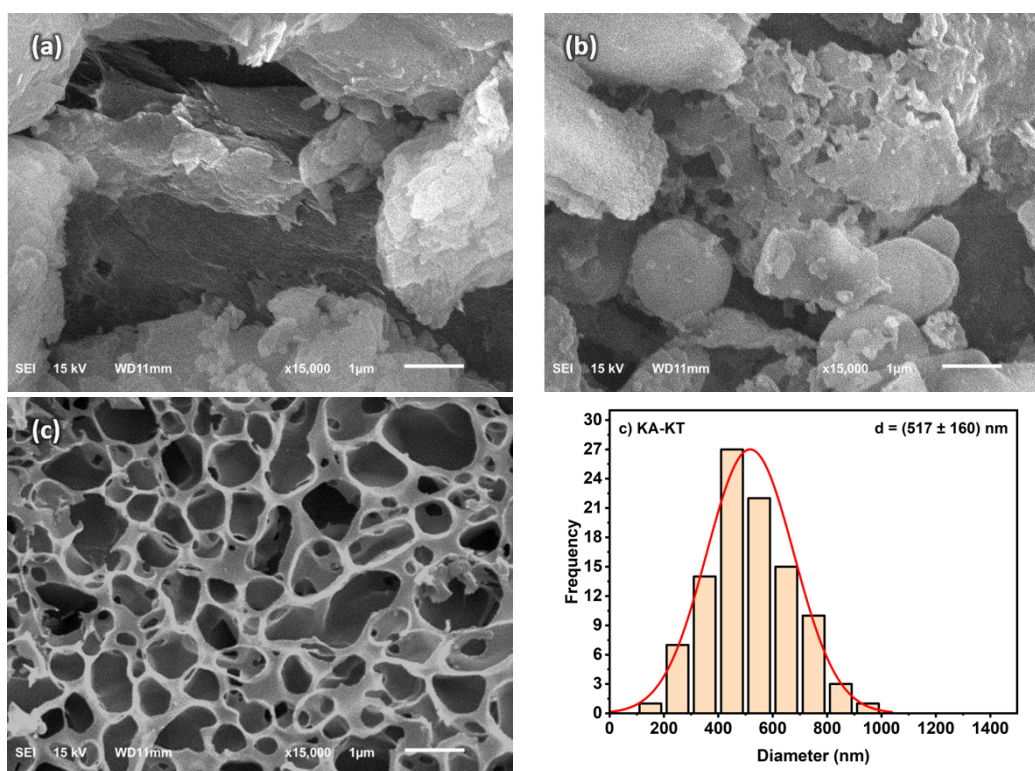
Importantly, the results do not support a general conclusion that nitrogen functionalization universally improves oxidative thermal stability. Instead, urea treatment modified the thermal response in a precursor-dependent manner. This behavior is consistent with recent reports showing that chemical functionalization of biomass-derived activated carbon can reorganize surface functional groups and porous structure without necessarily producing a proportional enhancement in thermal stability (19,22).

The precursor-dependent TGA response is qualitatively consistent with the complementary characterization results. FTIR indicated changes in oxygen- and nitrogen-containing surface functionalities following activation and urea treatment, while SEM–ImageJ revealed different morphological responses of the inner-wood- and bark-derived carbons (23). However, these thermal and morphological changes did not translate directly into CO₂ uptake, as evidenced by the contrasting CO₂-TPD responses of the two precursors. Collectively, these observations indicate that urea functionalization simultaneously modifies surface chemistry, morphology, and oxidative behavior, with the magnitude and consequence of these changes being strongly precursor-dependent.

Overall, TGA demonstrates that the oxidative thermal behavior of tembesu-derived activated carbons is controlled by both precursor type and subsequent surface functionalization. KA-KT exhibited substantially greater low-temperature moisture/volatile loss than KA-KKT, whereas urea treatment markedly reduced this contribution for the inner-wood-derived carbon but produced only a minor change for the bark-derived material. During subsequent oxidative heating, all samples underwent extensive consumption of the carbonaceous framework. Together with FTIR, SEM, XRD, and CO₂-TPD, these findings support a precursor-dependent structure–surface chemistry–thermal response relationship rather than providing evidence for a universal improvement in oxidative thermal stability following urea functionalization.

3.2. Scanning Electron Microscopy (SEM)

SEM analysis was carried out with a magnification of 15,000x each on the activated carbon material from tembesu wood waste. The sample was divided into two parts, namely a) wood (KT) and b) bark (KKT), with morphological results shown in Figure 3.



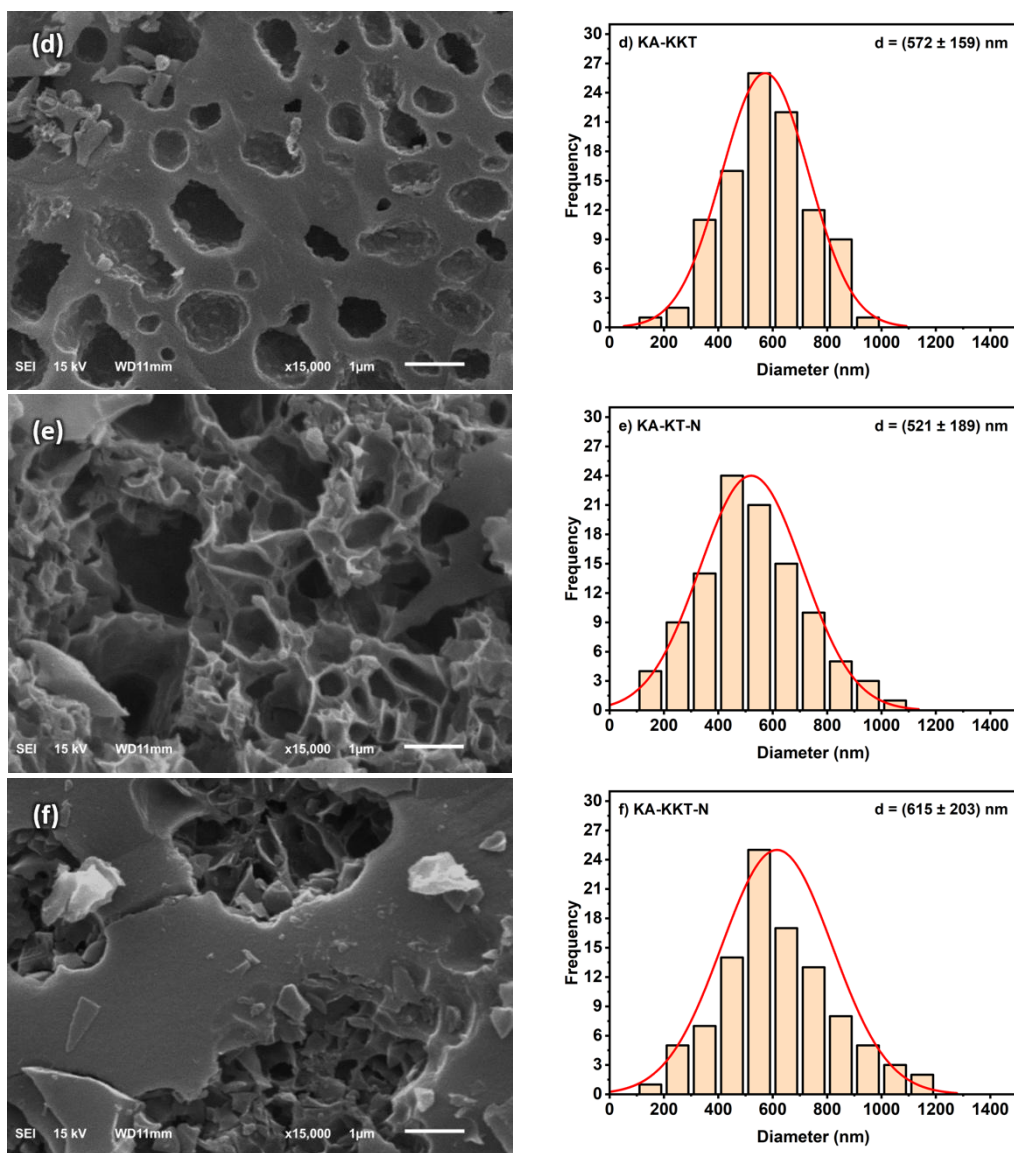


Figure 3. SEM micrographs of tembesu-derived carbon materials recorded at 15,000 $\times$ magnification: (a) HC-KT, (b) HC-KKT, (c) KA-KT, (d) KA-KKT, (e) KA-KT-N, and (f) KA-KKT-N. Insets in panels (c), (d), (e), and (f) show the distributions of apparent surface pore-opening diameters determined from the SEM micrographs using ImageJ.

ImageJ analysis was further employed to provide a semi-quantitative assessment of the apparent surface pore-opening diameters observed in the SEM micrographs. The mean pore-opening diameters were $517 \pm 160 \text{ nm}$ for KA-KT, $572 \pm 159 \text{ nm}$ for KA-KKT, $521 \pm 189 \text{ nm}$ for KA-KT-N, and $615 \pm 203 \text{ nm}$ for KA-KKT-N. These values represent the two-dimensional dimensions of pore openings visible on the external carbon surface at the applied SEM magnification and should be interpreted as morphological descriptors rather than intrinsic micro- or mesopore sizes.

The activated carbon derived from the two biomass fractions showed different pore-opening characteristics. KA-KKT had a larger mean apparent pore-opening diameter ($572 \pm 159 \text{ nm}$) than KA-KT ($517 \pm 160 \text{ nm}$), corresponding to an increase of approximately 10.6%. However, the SEM micrographs indicate that KA-KT possessed a more interconnected cellular or honeycomb-like morphology, while KA-KKT showed comparatively isolated pore openings embedded within a denser carbon matrix. This observation demonstrates that pore-opening diameter alone does not fully describe the overall porous architecture of the material. Differences in the morphological characteristics of biomass-derived activated carbon are strongly influenced by the chemical and structural nature of the precursors, as recently demonstrated for activated carbon obtained from different plant residues (24).

Urea treatment affected the pore-opening distributions differently depending on the biomass precursor. For the inner-wood-derived carbon, the mean pore-opening diameter changed only slightly from 517 ± 160 nm for KA-KT to 521 ± 189 nm for KA-KT-N, corresponding to an increase of less than 1%. However, the larger standard deviation observed for KA-KT-N indicates a broader and more heterogeneous distribution of surface pore openings following urea treatment. This observation is consistent with the visually more irregular surface morphology of KA-KT-N compared to KA-KT.

A more pronounced change was observed for the bark-derived carbon. The mean apparent pore-opening diameter increased from 572 ± 159 nm for KA-KKT to 615 ± 203 nm for KA-KKT-N, corresponding to a rise of approximately 7.5%. At the same time, the broader distribution of KA-KKT-N indicates increased morphological heterogeneity after urea treatment (25). These results suggest that the morphological response to nitrogen functionalization was precursor-dependent. Recent studies have similarly shown that urea-assisted modification can alter the surface morphology, textural properties, and accessibility of biomass-derived activated carbon, although the direction and magnitude of these changes strongly depend on the precursor and treatment conditions (26, 27).

Importantly, the apparent pore-opening diameters measured from SEM images should not be directly equated with the intrinsic pore-size distribution relevant to gas adsorption. The openings observed are predominantly in the submicrometre range, while CO_2 adsorption by activated carbon is strongly influenced by microporous and ultramicroporous domains that cannot be quantitatively resolved using conventional SEM imaging. Recent investigations of K_2CO_3 -activated biomass carbon have demonstrated that the development of microporous architecture plays a critical role in CO_2 adsorption performance (28).

Overall, the combined SEM and ImageJ results demonstrate that both the biomass precursor and urea treatment affected the surface architecture of tembesu-derived activated carbon. K_2CO_3 activation generated well-developed visible surface openings, particularly the interconnected cellular morphology observed for KA-KT, while subsequent urea treatment produced precursor-dependent morphological reorganization. The minimal change in mean pore-opening diameter for KA-KT-N and the comparatively larger increase observed for KA-KKT-N further indicate that the effect of nitrogen functionalization cannot be generalized across the two biomass fractions.

3.3. Fourier Transform Infrared (FTIR) Spectroscopy

Fourier transform infrared spectroscopy was employed to evaluate the evolution of surface functional groups during hydrothermal carbonization, K_2CO_3 activation, and subsequent urea treatment of the inner-wood- and bark-derived tembesu carbon. The spectra were recorded within the range of $4000\text{--}750\text{ cm}^{-1}$, as presented in Figure 4. Distinct changes in band position and spectral profile were observed among the hydrochar (HC-KT and HC-KKT), activated carbon (KA-KT and KA-KKT), and nitrogen-functionalized samples (KA-KT-N and KA-KKT-N), indicating progressive modification of the lignocellulose-derived chemical structure during the successive treatments.

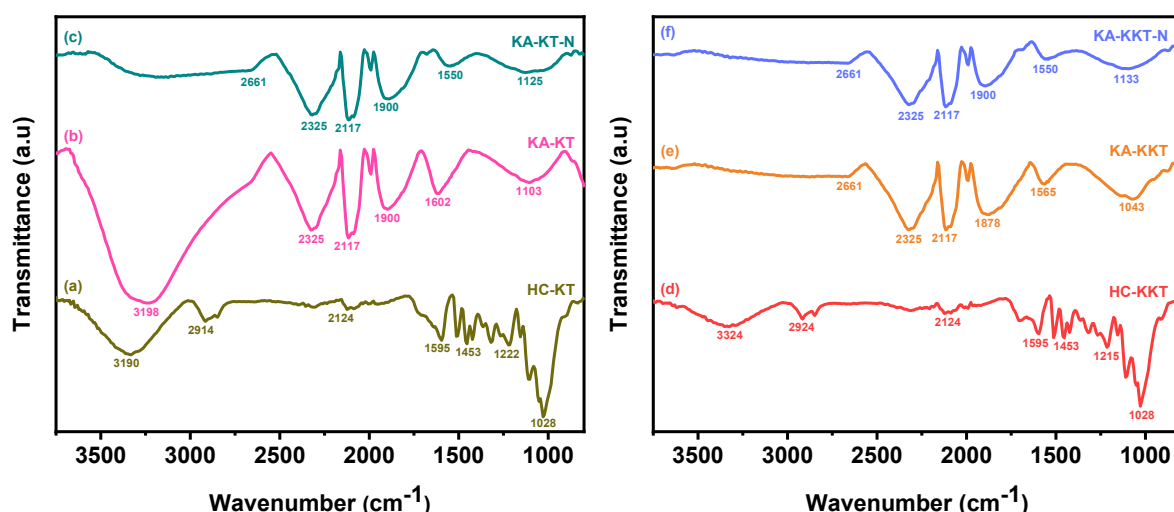


Figure 4. FTIR spectra of tembesu-derived carbon materials: (a) HC-KT, (b) KA-KT, (c) KA-KT-N,

(d) HC-KKT, (e) KA-KKT, and (f) KA-KKT-N. Spectra illustrate the evolution of surface functional groups following hydrothermal carbonization, K_2CO_3 activation, and subsequent urea treatment.

The FTIR spectra of the hydrochar retained several characteristic features associated with lignocellulose-derived structures. HC-KT showed bands at approximately 3190, 2914, 2124, 1595, 1453, 1222, and 1028 cm^{-1} , while HC-KKT had corresponding features at approximately 3324, 2924, 2124, 1595, 1453, 1215, and 1028 cm^{-1} . The broad bands centered at approximately 3190 cm^{-1} for HC-KT and 3324 cm^{-1} for HC-KKT are assigned mainly to hydrogen-bonded O–H stretching vibrations associated with hydroxyl-containing lignocellulosic structures and adsorbed moisture. The bands at 2914 and 2924 cm^{-1} are attributed to aliphatic C–H stretching of $-CH_2$ and $-CH_3$ groups, respectively. The persistence of these bands indicates incomplete removal of lignocellulose-derived functionalities during HTC at 160 °C. Differences between HC-KT and HC-KKT are consistent with the precursor-dependent chemical behavior previously reported for wood- and bark-derived hydrochar (20,29).

K_2CO_3 activation substantially modified the FTIR profiles. KA-KT showed bands at 3198, 2325, 2117, 1900, 1602, and 1103 cm^{-1} , whereas KA-KKT showed bands at 2661, 2325, 2117, 1878, 1565, and 1043 cm^{-1} . The reduction or disappearance of several lignocellulose-related bands and the persistence of signals near 1602–1565 cm^{-1} indicate structural rearrangement toward a more aromatic carbon framework while retaining oxygen-containing surface functionalities. The bands at 1103 and 1043 cm^{-1} are mainly assigned to residual C–O-containing groups. These chemical changes complement the SEM observations, which showed pronounced development of visible surface openings after K_2CO_3 activation, particularly the interconnected honeycomb-like morphology of KA-KT. K_2CO_3 activation has similarly been shown to promote extensive pore development in biomass-derived carbon (25).

The band at approximately 2325 cm^{-1} is close to the asymmetric stretching region of CO_2 . However, it was not considered direct evidence of adsorption because environmental CO_2 contributes to signals near 2350 cm^{-1} in FTIR measurements (30). The weak features at 2117–2124 and 1878–1900 cm^{-1} were also retained as experimentally observed bands but were not assigned to specific functional groups because of their limited specificity in complex carbonaceous materials.

Urea treatment produced additional spectral changes, with KA-KT-N showing bands at 2661, 2325, 2117, 1900, 1550, and 1125 cm^{-1} , while KA-KKT-N had bands at 2661, 2325, 2117, 1900, 1550, and 1133 cm^{-1} . The band near 1550 cm^{-1} may be attributed to N–H bending and C–N-containing functionalities, although overlap with aromatic C=C vibrations cannot be excluded. Similarly, the bands at 1125–1133 cm^{-1} are consistent with possible C–N contributions but may overlap with C–O vibrations. The spectral changes support nitrogen functionalization after urea treatment, but FTIR alone cannot unequivocally establish nitrogen incorporation or its chemical configuration. Recent studies of urea-treated biomass carbon combine FTIR with XPS and elemental analysis to confirm nitrogen retention and speciation (23).

The FTIR observations are also consistent with the TGA and SEM results. KA-KT showed the highest initial TGA mass loss (26.79%), compared to 9.17% for KA-KKT, indicating different moisture/volatile affinities associated with their surface chemistry. After urea treatment, the initial losses decreased to 15.83% for KA-KT-N and 8.67% for KA-KKT-N, supporting modification of the surface chemical environment. Morphologically, SEM–ImageJ analysis showed apparent pore-opening diameters of 517 ± 160 , 572 ± 159 , 521 ± 189 , and 615 ± 203 nm for KA-KT, KA-KKT, KA-KT-N, and KA-KKT-N, respectively. The nearly unchanged mean pore opening of KA-KT after urea treatment, compared to the larger increase for KA-KKT-N, further suggests a precursor-dependent response to functionalization.

Overall, FTIR confirms progressive chemical transformation from lignocellulose-rich hydrochar to chemically reorganized activated carbon and subsequently to urea-functionalized materials. Combined FTIR, TGA, and SEM results demonstrate that K_2CO_3 activation and urea treatment modify the surface chemistry, oxidative thermal behavior, and external morphology of tembesu-derived carbon in a precursor-dependent manner.

3.4. X-Ray Diffraction (XRD)

XRD analysis was performed to evaluate the structural evolution of tembesu-derived carbon during hydrothermal carbonization, K_2CO_3 activation, and subsequent urea treatment (Figure 5). The hydrochar retained relatively well-defined diffraction features. HC-KT showed peaks at approximately 16.04°, 22.84°, and 26.94°, while HC-KKT had reflections at approximately 16.1°, 22.3°, and 34.6°. The peaks around 16° and 22° are characteristic of

crystalline cellulose-I domains, indicating that hydrothermal carbonization at 160 °C for 6 h did not completely disrupt the native cellulose structure. Similar persistence of cellulose-related diffraction after relatively mild hydrothermal treatment has recently been reported for lignocellulosic biomass, while the extent of structural transformation depends strongly on precursor composition and HTC severity (31).

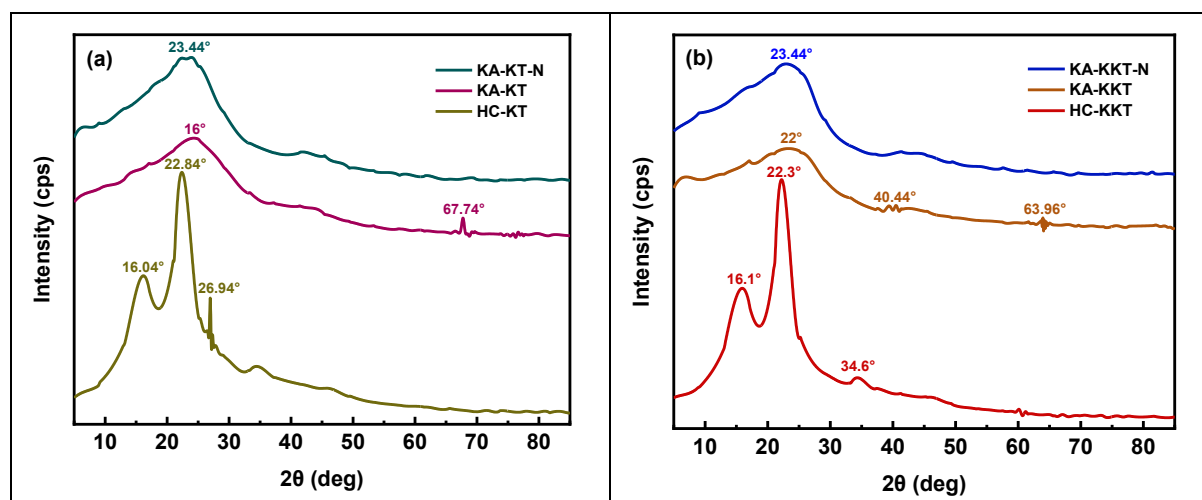


Figure 5. XRD patterns of tembesu-derived carbon materials: (a) HC-KT, KA-KT, and KA-KT-N; and (b) HC-KKT, KA-KKT, and KA-KKT-N. The broad diffraction features of the activated and urea-treated samples indicate predominantly disordered/turbostratic carbon structures.

The additional reflections at 26.94° for HC-KT and 34.6° for HC-KKT were experimentally observed but not assigned unequivocally because biomass-derived hydrochar may contain overlapping contributions from residual crystalline organic and inorganic components. Therefore, definitive phase assignment would require comparison with appropriate reference diffraction patterns or complementary elemental/mineralogical analysis.

K₂CO₃ activation markedly reduced the sharp cellulose-related diffraction features and produced broader diffraction profiles, indicating substantial disruption of the ordered lignocellulosic structure. Following urea treatment, broad maxima were observed at approximately 23.44° for KA-KT-N and 23° for KA-KKT-N. Broad reflections in the approximately 20–25° region are commonly associated with the (002) disordered or turbostratic carbon, reflecting limited stacking order of graphene-like carbon domains rather than a highly crystalline graphitic structure (32).

The XRD evolution is consistent with the complementary FTIR and SEM observations. FTIR showed attenuation of lignocellulose-related C–H and C–O functionalities after K₂CO₃ activation and a greater contribution from aromatic carbon structures, while SEM demonstrated pronounced development of an open porous surface, particularly the interconnected honeycomb-like morphology of KA-KT. Therefore, XRD confirms loss of long-range structural order, while FTIR and SEM demonstrate simultaneous chemical and morphological reorganization of the carbon matrix.

Urea treatment further broadened the diffraction features but should not, based on XRD alone, be interpreted as direct evidence of nitrogen doping. Instead, the XRD results indicate increased structural disorder after functionalization. This interpretation is supported by the FTIR changes near 1550 and 1125–1133 cm^{−1}, which are consistent with possible nitrogen-containing surface functionalities, and by the altered SEM morphology. Recent studies have similarly shown that urea treatment can simultaneously modify nitrogen chemistry and pore development, although direct identification of nitrogen species requires XPS or elemental analysis (23).

Overall, the combined XRD, FTIR, and SEM results demonstrate a transition from cellulose-containing hydrochar to structurally disordered, porous activated carbon. K₂CO₃ activation was primarily responsible for destroying the residual ordered lignocellulosic structure and developing the porous carbon framework, while subsequent urea treatment produced additional, precursor-dependent structural and surface modifications.

3.5. CO₂ Adsorption and Temperature-Programmed Desorption

CO₂ capture test was conducted to determine how effectively carbon from tembesu wood waste can capture CO₂ gas. This test was carried out by examining the effect of temperature on the thermal conductivity and adsorption capacity of each sample, as shown in Figure 6.

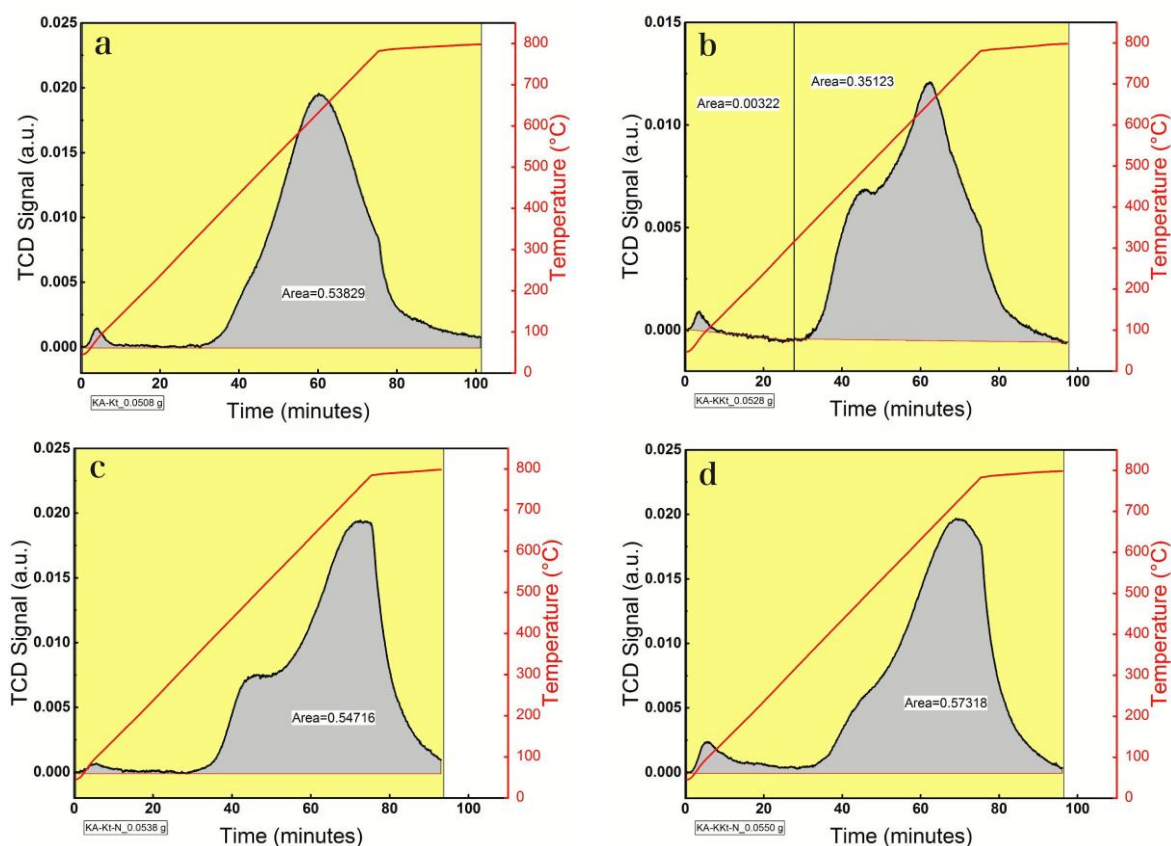


Figure 6. CO₂ temperature-programmed desorption (CO₂-TPD) profiles of (a) KA-KT, (b) KA-KKT, (c) KA-KT-N, and (d) KA-KKT-N.

CO₂ adsorption–desorption behavior was evaluated using temperature-programmed desorption (CO₂-TPD). Initially, the samples were pretreated at 350 °C for 60 min under an inert atmosphere. CO₂ adsorption was subsequently performed using 5% CO₂ in He at 40 °C for 30 min, followed by He purging at the same temperature for 30 min. The adsorbed CO₂ was desorbed from 40 to 800 °C at a heating rate of 10 °C min^{−1} under He, with all gas flow rates maintained at 50 mL min^{−1}.

The results presented in the CO₂-TPD profiles showed significant differences in both the amount and temperature distribution of desorbed CO₂. KA-KT demonstrated a broad high-temperature desorption profile and a CO₂ uptake of 2.1844 mmol g^{−1}, while KA-KKT showed a considerably lower value of 1.3835 mmol g^{−1}. The high-temperature TPD contributions are consistent with relatively strong CO₂–surface interactions. However, since oxygen-containing surface functionalities can also evolve CO₂ during thermal treatment of carbon materials, these features should not be assigned exclusively to strong basic sites (33).

Urea treatment produced markedly different effects depending on the precursor. The CO₂ uptake of KA-KT-N was 2.0966 mmol g^{−1}, approximately 4.0% lower than KA-KT. In contrast, the capacity of KA-KKT increased from 1.3835 to 2.1485 mmol g^{−1} after urea treatment, corresponding to an enhancement of approximately 55.3%. The quantitative results are summarized in Table 4.

Table 4. CO₂ uptake of tembesu-derived activated carbon determined by CO₂-TPD and the effect of urea functionalization.

Sample	CO ₂ uptake (mmol g ⁻¹)	Effect of urea (%)	Interpretation
KA-KT	2.1844	—	Highest uptake among non-functionalized carbon
KA-KT-N	2.0966	-4.0	Slight decrease after urea treatment
KA-KKT	1.3835	—	Lowest uptake
KA-KKT-N	2.1485	+55.3	Marked enhancement after urea treatment

The results demonstrate that urea functionalization did not produce a universal enhancement in CO₂ uptake. For the inner-wood-derived carbon, the capacity decreased slightly by approximately 4.0%, while the bark-derived carbon showed a pronounced increase of approximately 55.3%. This contrasting behavior indicates that the effect of urea treatment was strongly dependent on the physicochemical characteristics of the biomass precursor. Similar precursor- and nitrogen-source-dependent behavior has recently been reported for K₂CO₃-activated sawdust-derived porous carbon, where CO₂ uptake was governed by a balance between nitrogen functionality and accessible narrow microporosity (34,35).

The adsorption trend is also consistent with the complementary structural characterization. Although KA-KKT showed a larger SEM-derived apparent pore-opening diameter than KA-KT, the CO₂ uptake was substantially lower, indicating that external pore-opening dimensions alone do not determine adsorption capacity. After urea treatment, KA-KKT-N showed both a larger apparent pore-opening diameter and substantially increased CO₂ uptake, together with FTIR evidence of modified nitrogen-containing surface functionalities and a disordered carbon structure observed by XRD. Recent studies similarly demonstrate that CO₂ adsorption in nitrogen-functionalized biomass carbon results from the combined effects of micropore architecture and nitrogen-containing surface chemistry rather than either factor independently (36).

Overall, the results establish a clear precursor–structure–functionalization–CO₂ interaction relationship. K₂CO₃ activation alone produced an effective CO₂ adsorbent from inner wood, while bark-derived carbon responded significantly more strongly to subsequent urea functionalization. This precursor-dependent behavior constitutes an important result and indicates that nitrogen functionalization should be optimized according to the physicochemical characteristics of the original biomass rather than applied as a universally beneficial modification strategy.

Conclusion

In conclusion, this study demonstrates that tembesu wood waste can be converted into CO₂-adsorbing activated carbon through hydrothermal carbonization and K₂CO₃ activation, while the effect of subsequent urea functionalization is strongly precursor-dependent. Structural analyses showed the transformation of lignocellulose-derived hydrochar into disordered porous carbon frameworks, accompanied by changes in surface chemistry, morphology, and oxidative thermal behavior. KA-KT demonstrated the highest CO₂ uptake among the non-functionalized carbon (2.1844 mmol g⁻¹), while urea treatment slightly decreased the uptake of KA-KT-N to 2.0966 mmol g⁻¹. In contrast, the bark-derived carbon showed a pronounced improvement from 1.3835 mmol g⁻¹ for KA-KKT to 2.1485 mmol g⁻¹ for KA-KKT-N, corresponding to an enhancement of approximately 55.3%. These results demonstrate that urea functionalization should be optimized according to the chemical and structural characteristics of the biomass precursor rather than regarded as a universally beneficial treatment. Overall, both inner wood and bark of tembesu waste are promising precursors for CO₂ adsorbents, with K₂CO₃ activation being sufficient for inner wood and urea functionalization providing a particularly strong benefit for bark-derived carbon.

Author Contribution

Conceptualization: IR, ASFR, WM, FM; experimental: SF, NC; writing and preparation of original draft: IR, WM, NC, SF, MR; and writing including review and editing: FM, ASFR. All authors have read and agreed to the published version of the manuscript.

Funding

This study was funded by the Indonesian Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology, and managed under the EQUITY Program 2025-2026 with Decree Number: 0030/UN9.R/SK.R3.LPPM/2025, on November 10, 2025.

Declaration

Consent for publication: All authors read and approved the final manuscript for publication.

Competing interests: The authors declare that there are no competing interests.

Conflict of interest: The authors declare that there are no conflicts of interest.

Ethics approval: This study did not require local ethics committee approval.

Consent to participate: All authors read and approved the final manuscript.

Availability of Data and Materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

REFERENCES

1. Kabir M, Habiba U, Iqbal MZ, Shafiq M, Farooqi ZR, Shah A, et al. Impacts of anthropogenic activities & climate change resulting from increasing concentration of Carbon dioxide on the environment in 21 st Century ; A Critical Review. IOP Conf Ser Earth Environ Sci. 2023;(1194):1–7.
2. Madejski P, Chmiel K, Subramanian N. Methods and Techniques for CO₂ Capture : Review of Potential. Energies. 2022;15:1–21.
3. Quan C, Chu H, Zhou Y, Su S, Su R, Gao N. Amine-modified silica zeolite from coal gangue for CO₂ capture. Fuel [Internet]. 2022;322(April):124184. Available from: <https://doi.org/10.1016/j.fuel.2022.124184>
4. Gan F, Wang B, Jin Z, Xie L, Dai Z, Zhou T, et al. From typical silicon-rich biomass to porous carbon-zeolite composite : A sustainable approach for efficient adsorption of CO₂. Sci Total Environ [Internet]. 2021;768:144529. Available from: <https://doi.org/10.1016/j.scitotenv.2020.144529>
5. Kordala N, Wyszowski M. Zeolite Properties, Methods of Synthesis, and Selected Applications. Molecules. 2024;29:1–25.
6. Tatlier M, Atalay-oral C, Bayrak A, Maras T. Thermochemica Acta: Impact of ion exchange on zeolite hydrophilicity/hydrophobicity monitored by water capacity using thermal analysis. Thermochem Acta. 2022;713:1–8.
7. Li H, Hu C, He Y, Sun Z, Yin Z, Tang D. Emerging surface strategies for porous materials-based phase change composites. Matter [Internet]. 2022;5(10):3225–59. Available from: <https://doi.org/10.1016/j.matt.2022.07.013>
8. Yew S, Chai W, Ngu LH, How BS, Engineering F. Review of carbon capture absorbents for CO₂ utilization. Greenh Gases Sci Technol. 2022;11(5):394–427.
9. Wang S sian, Hsu C han, Tsai C ta, Lin H ping, Yan C wei, Chang J kuei, et al. Conversion of wood waste into nitrogen-doped graphite-like multiporous carbon with high specific surface area and electrical conductivity for high Sustainable Energy Fuels [Internet]. 2025;9:2355–68. Available from: [rsc.li/sustainable-energy/](https://www.rsc.li/sustainable-energy/)
10. Ting H, Bing F, Peipei LU, Zhongliang Z, Qi NIU, Zonghu MA, et al. Hydrothermal N-doping assisted synthesis of poplar sawdust-derived porous carbon for carbon capture. J Fuel Chem Technol [Internet]. 2025;53(8):1191–202. Available from: [http://dx.doi.org/10.1016/S1872-5813\(25\)60533-0](http://dx.doi.org/10.1016/S1872-5813(25)60533-0)
11. Ivanova S, Vesnina A, Fotina N, Prosekov A. An Overview of Carbon Footprint of Coal Mining to Curtail Greenhouse Gas Emissions. Sustainability. 2022;1–22.
12. Yong JB, Tan LS, Tan J. Comparative life cycle assessment of biomass-based and coal-based activated carbon production. Prog Energy Environ. 2022;20:1–15.
13. Mokhtar N, Razali SM, Sulaiman MS, Edin T, Wahab R. Converting wood-related waste materials into other value-added products : A short review Converting wood-related waste materials into other value-added products : A short review. Earth Environ Sci. 2022;1–8.
14. Troncoso OP, Sari RM, Torres FG, De-la-torre GE, Gea S. Analysis and availability of lignocellulosic wastes : Assessments for Indonesia and Peru. Env Qual Manag. 2021;(December 2020):1–12.
15. Haryanto A, Hidayat W, Hasanudin U, Iryani dewi agustina, Kim S, Lee S, et al. Valorization of Indonesian Wood Wastes through Pyrolysis : A Review. Energies. 2021;1–25.
16. Darlis VV, Siahaan H, Mardhiansyah M. Pengaruh Pupuk Organik Cair Bonggol Pisang terhadap Pertumbuhan Tanaman Tembesu (Fagraea fragrans). J Educ Dev. 2024;12(1):333–7.
17. Rattanaburi S, Kaikaew K, Watanapokasin R, Phongpaichit S, Mahabusarakamb W. A new lignan from the stem bark of Fagraea fragrans Roxb. Nat Prod Res [Internet]. 2020;0(0):1–6. Available from:

- <https://doi.org/10.1080/14786419.2020.1821020>
18. Yang H, Yu Y, Zhang H, Wang W, Zhu J, Chen Y, Zhang S, Chen H. Effect mechanism of phosphorous-containing additives on carbon structure evolution and biochar stability enhancement. *Biochar*. 2024;6:39. doi:10.1007/s42773-024-00330-5.
 19. Marino A, Poselle Bonaventura C, Sciarretta S, Conte G, Pelosi C, Lazzarini A, Aloise A, Duce C, Bernazzani L, Policicchio A, Crucianelli M. Solvent effects in biomass-derived activated carbon: New insights for their doping/functionalization toward potential hydrogen storage applications. *Langmuir*. 2025;41(20):12619–12633. doi:10.1021/acs.langmuir.5c00711.
 20. Inkoua S, Li C, Gao G, Zhang L, Zhang S, Tang Y, Wang D, Leng C, Hu X. Thermal treatment of wood, bark and leaves of same poplar tree through hydrothermal carbonization and activation: Roles of aliphatic structures in pore development. *Biomass and Bioenergy*. 2024;182:107101. doi:10.1016/j.biombioe.2024.107101.
 21. Guizani C, Widsten P, Siipola V, Paalijärvi R, Berg J, Pasanen A, Kalliola A, Torvinen K. New insights into the chemical activation of lignins and tannins using K_2CO_3 —a combined thermoanalytical and structural study. *Carbon Letters*. 2024;34(1):371–386. doi:10.1007/s42823-023-00601-4.
 22. Kerimkulova A, Yermoldanov Y, Sabitov A, Velasco LF, Asanbek N, Kubaiden A, Zhumagaliyeva A, Mansurov Z, Atamanov M, Nysanbayeva G, Yermolenko V, Doszhanov O. Use of urea-modified activated carbon sorbents derived from plant residues for gas sorption. *Applied Sciences*. 2026;16(13):6812. doi:10.3390/app16136812.
 23. Arauzo PJ, Checa-Gómez M, De Smedt J, Van Cleemput A, Maziarka PA, Nicolae SA, Ronsse F. Effects of activation route and doping on porosity and nitrogen retention on natural fibers. *Biomass and Bioenergy*. 2026;209:108992. doi:10.1016/j.biombioe.2026.108992.
 24. Khuong DA, Trinh KT, Nakaoka Y, Tsubota T, Tashima D, Nguyen HN, Tanaka D. The investigation of activated carbon by K_2CO_3 activation: Micropores- and macropores-dominated structure. *Chemosphere*. 2022;299:134365. doi:10.1016/j.chemosphere.2022.134365.
 25. Xu Y, Liu Y, Zhan W, Zhang D, Liu Y, Xu Y, Wu Z. Enhancing CO_2 capture with K_2CO_3 -activated carbon derived from peanut shell. *Biomass and Bioenergy*. 2024;183:107148. doi:10.1016/j.biombioe.2024.107148.
 26. Karadirek Ş, Kanmaz N, Tuna Ö, Demircivi P. Designing of N/O heteroatoms doped biomass-derived activated carbon for boosting toxic dye pollutant adsorption. *Biomass and Bioenergy*. 2025;199:107968. doi:10.1016/j.biombioe.2025.107968.
 27. Sreńscek-Nazzal J, Kamińska A, Serafin J, Michalkiewicz B. Chemical activation of banana peel waste-derived biochar using KOH and urea for CO_2 capture. *Materials*. 2024;17(4):872. doi:10.3390/ma17040872.
 28. Xu Y, Zhang D, Liu Y, Xu Y, Meng W, Zhong J, Hu R, Wu Z. Elucidating the role of moderate K_2CO_3 activation in tuning microporous architecture of bamboo-derived carbon for superior CO_2 capture. *Biomass and Bioenergy*. 2025;201:108140. doi:10.1016/j.biombioe.2025.108140.
 29. Wu S, Wang Q, Cui D, Wu D, Bai J, Qin H. Insights into the chemical structure evolution and carbonisation mechanism of biomass during hydrothermal treatment. *Journal of the Energy Institute*. 2023;108:101257. doi:10.1016/j.joei.2023.101257.
 30. Tseng TR, Yang CH, Lu HC, Liu CP, Cheng BM. Analysis of carbon materials with infrared photoacoustic spectroscopy. *Analytical Chemistry*. 2024;96(26):10732–10737. doi:10.1021/acs.analchem.4c01797.
 31. Zhou J, Fang Z, Chen K, Cui J, Yang D, Qiu X. Improving the degree of polymerization of cellulose nanofibers by largely preserving native structure of wood fibers. *Carbohydrate Polymers*. 2022;296:119919. doi:10.1016/j.carbpol.2022.119919.
 32. Dziejarski B, Serafin J, Hernández-Barreto DF, Naumovska E, Sreńscek-Nazzal J, Klomkliang N, Tam E, Krzyżyńska R, Andersson K, Knutsson P. Tailoring highly surface and microporous activated carbon (ACs) from biomass via KOH, $K_2C_2O_4$ and KOH/ $K_2C_2O_4$ activation for efficient CO_2 capture and CO_2/N_2 selectivity: Characterization, experimental and molecular simulation insights. *Chemical Engineering Journal*. 2025;524:169677. doi:10.1016/j.cej.2025.169677.
 33. Appiah FA, Nugloze D, Sai-Obodai LS, Natewong P, Idem RO. Activated carbon produced from the hydrothermal treatment of glucose with KOH activation for catalytic absorption of CO_2 in a BEA–AMP bi-solvent blend. *ACS Omega*. 2023;8(10):9346–9355. doi:10.1021/acsomega.2c07758.
 34. Mochizuki Y, Bud J, Byambajav E, Tsubouchi N. Pore properties and CO_2 adsorption performance of activated carbon prepared from various carbonaceous materials. *Carbon Resources Conversion*. 2025;8(1):100237. doi:10.1016/j.crcon.2024.100237.
 35. Ma X, Xu W, Xue R, Su C, Su R, Li X, Zeng Z, Li L. Effect of mechanical compaction and nitrogen doping treatment on ultramicropore structure of biomass-based porous carbon and the mechanism of CO_2 capture. *Chemical Engineering Science*. 2025;303:120995. doi:10.1016/j.ces.2024.120995.

36. Zhang H, Jiang F, Zhang X, Hu S, Li J, Zhang H, Liu K. CO₂ adsorption performance of nitrogen-doped activated carbon from banana pseudo-stem by urea-assisted high-pressure CO₂-hydrothermal treatment. *Separation and Purification Technology*. 2025;366:132773. doi:10.1016/j.seppur.2025.132773.