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Biochar-based carbon sequestration: physicochemical characterization and Assessment of carbon stability

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Method Article

Keywords: Biochar, carbon stability, pyrolysis, wood biomass, carbon storage

Posted Date: September 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10999689/v1

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Additional Declarations: The authors declare potential competing interests as follows: ok

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Abstract

Biochar has attracted a lot of attention as a possible carbon-sequestration material because pyrolysis converts carbon produced from biomass into an extremely durable, carbon-rich solid. This work evaluated the carbon-stability characteristics of wood-derived biochar produced by slow pyrolysis at 700 °C for 5 hours under oxygen-limited conditions using thorough physicochemical characterization. The structural, chemical, morphological, elemental, and surface properties were assessed using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM–EDX), and Brunauer–Emmett–Teller (BET) analysis. While FTIR revealed distinctive hydroxyl, aliphatic C–H, and oxygen-containing functional groups, the XRD pattern revealed a mostly disordered structure with crystalline and mineral-associated phases. A surface morphology with pores and interparticle spaces was found to be uneven and diverse by SEM. 85.91 weight percent C, 9.34 weight percent O, and 4.74 weight percent Ca were displayed by EDX. A heterogeneous porous structure with nitrogen adsorption reaching around 140 cm^3 STP g^{-1} was revealed by BET analysis. Overall, the findings show that the generated biochar has qualities that are advantageous for carbon stabilization and possible long-term carbon storage. However, to quantitatively confirm carbon persistence, field research and long-term incubation are needed.

Keywords: Biochar; carbon stability; pyrolysis; wood biomass; carbon storage.

1. Introduction

There is a pressing need for efficient methods of mitigating climate change and long-term carbon storage due to the rising atmospheric concentration of carbon dioxide (CO_2). The process of capturing and holding onto carbon in comparatively stable reservoirs to slow down its quick return to the atmosphere is known as carbon sequestration. Soil is a significant carbon reservoir in terrestrial ecosystems, and converting renewable biomass into stable carbonaceous materials has shown promise as a way to improve carbon storage [1]. Biochar is a carbon-rich solid that is created when biomass is thermochemically converted in an oxygen-limited environment. The main biomass components—cellulose, hemicellulose, and lignin—undergo thermal breakdown during pyrolysis, which releases volatile chemicals and concentrates

carbon in the solid fraction. Compared to the original biomass, the resulting biochar typically has more condensed and aromatic carbon structures, which can strengthen its resistance to biological breakdown and help retain carbon over time. However, the properties of the generated biochar and the pyrolysis conditions have a significant impact on the amount and durability of carbon storage [2].

In particular, pyrolysis temperature and residence time have a significant impact on biochar output, carbon concentration, degree of carbonization, aromaticity, surface properties, and structural stability. Although it may potentially lower the output of biochar, increasing the intensity of pyrolysis often encourages the elimination of volatile components and the formation of condensed carbon structures. Therefore, both the amount of carbon retained and the physicochemical properties related to its persistence must be taken into account when evaluating the carbon-sequestration capability of biochar [3].

Therefore, a thorough characterisation method is necessary to comprehend the characteristics that cause carbon stabilization. While Fourier transform infrared spectroscopy (FTIR) detects functional groups and chemical changes, X-ray diffraction (XRD) offers information on crystalline mineral phases and structural structure. Energy-dispersive X-ray spectroscopy (EDX) ascertains the elemental composition of the material under study, while scanning electron microscopy (SEM) offers details on surface shape and pore growth. While thermogravimetric analysis (TGA) can be used to evaluate thermal breakdown behavior and the relative thermal resistance of carbonaceous fractions, Brunauer–Emmett–Teller (BET) analysis offers information on surface area and pore properties [4]. The combination of these methods can therefore offer a more thorough evaluation of biochar properties than any one analytical technique alone. Carbon persistence is mostly dependent on pyrolysis, which converts biomass into a more condensed carbon structure. A carbon fraction that is more resistant to degradation may result from the breakdown of comparatively labile organic components and the creation of aromatic and condensed structures. However, since the behavior of biochar after soil application can be influenced by microbial activity, moisture, temperature, mineral interactions, oxidation, and aging processes, laboratory-derived indicators of recalcitrance should be interpreted as evidence of carbon-stability potential rather than direct measurements of field persistence [5].

Through their interactions with the carbonaceous matrix, mineral elements may have further effects on carbon stability. The physicochemical characteristics of biochar and its interactions

with soil minerals and organic matter after application may be influenced by elements that are retained during pyrolysis. As a result, elemental and mineral characterization offers more details for comprehending the possible processes controlling carbon retention [6].

In order to fully comprehend biochar's potential contribution to long-term carbon storage, an integrated evaluation of its structural, chemical, morphological, elemental, and surface properties is necessary, despite the growing interest in it for carbon management. In this study, wood biomass was slowly pyrolyzed at 700 °C for five hours under oxygen-limited circumstances to produce biochar. The generated material's structural, chemical, morphological, elemental, and surface properties in connection with carbon stabilization were assessed using XRD, FTIR, SEM–EDX, and BET analysis [7]. This multi-analytical method makes it easier to evaluate how higher treatment temperatures improve pore formation and aromaticity, two important markers of long-term recalcitrance [8],[9]. Additionally, the relationship between molecular complexity and the effectiveness of biochar as a carbon-sequestration agent is made clear by this thorough structural interpretation [10]. The possibility of mineral-mediated protection through silica encapsulation, which could offer an extra physical barrier against microbial and abiotic degradation, deserves more research in addition to the inherent aromaticity of the carbon matrix [11]. Additionally, the development of Fe-O-C linkages and other organometallic complexes at the biochar-mineral interface can greatly increase surface oxidation resistance and further inhibit the mineralization of resistant carbon fractions [12]. The trade-offs between pyrolysis-induced carbonization and the possibility of secondary stabilization through soil-mineral interactions can be more precisely quantified by incorporating these analytical findings [13],[14]. Furthermore, sophisticated spectroscopic methods, like synchrotron-based Near-edge X-ray Absorption Fine Structure analysis, can distinguish between crystalline and amorphous chemical phases, giving a detailed understanding of how thermal history determines long-term chemical resilience [15]. Furthermore, these high-temperature conditions help create silicate-carbon complexes that are resistant to microbial degradation, thereby prolonging the duration that sequestered carbon stays in the soil matrix [16]. Wood-based feedstocks are especially advantageous for creating long-term carbon sinks because of their hierarchical stability, which extends from molecular-level aromatic compounds to macro-scale mineral-organic interactions [17]. Additionally, the degree of polycyclic aromatic hydrocarbon condensation attained during the thermochemical conversion is directly related to the biochars' intrinsic resistance to biotic degradation, which is a crucial component of their long-term sequestration efficacy [18],[19]. By greatly raising

carbon aromaticity, high-temperature pyrolysis facilitates this condensation, improving oxidation resistance and guaranteeing long-term persistence in soil conditions [20].

This study's goal was to assess wood-derived biochar's capacity for carbon stabilization using comprehensive physicochemical characterization. The particular goals were to:

1. Analyze the biochar's structural characteristics using XRD.
2. Use FTIR to determine the main functional groups.
3. Analyze surface morphology with an SEM.
4. Evaluate the elemental composition with EDX.
5. Assess the properties of the surface and pores using BET analysis.
6. Incorporate the physicochemical findings to evaluate the biochar's probable stability and long-term capacity to store carbon.

2. Materials and Methods

2.1 Feedstock collection and preparation

The wood biomass was physically cleaned of soil, stones, and other extraneous objects. Following cleaning, the biomass was oven-dried and then air-dried until it reached a uniform mass. The biomass was dried, then ground and sieved to provide a uniform particle size suitable for further processing. In order to modify the processed biomass and facilitate the removal of inorganic and other undesirable components, nitric acid (HNO_3) was employed. Following acid treatment, the biomass was thoroughly cleaned with distilled water and neutralized with sodium bicarbonate ($NaHCO_3$) until the pH of the material was roughly neutral. The treated biomass was then utilized for the pyrolysis process after being cleaned with distilled water to get rid of any remaining acid and salts. It was then dried once more to achieve a consistent mass.

2.2 Biochar production.

Slow pyrolysis in an oxygen-limited environment created biochar. The prepared biomass was heated to 700 °C at a rate of 5 °C min^{-1} in a muffle furnace using a stainless-steel tube (SS310). The sample spent five hours (300 minutes) at the desired temperature. Following pyrolysis, the furnace was left to cool in an oxygen-limited environment. Before being characterized, the resultant biochar was gathered, weighed, and kept in airtight containers. The calculation of biochar yield was:

$$Biochar\ yield(\%) = \frac{Mass\ of\ biochar}{Mass\ of\ dry\ feedstock} \times 100$$

Because temperature and residence time affect biochar output, carbon content, aromaticity, surface characteristics, and stability, choosing the right pyrolysis conditions is crucial. In order to encourage significant carbonization and the development of a stable, carbon-rich biochar structure appropriate for long-term carbon sequestration, this study used a temperature of 700 °C and a residence duration of 5 hours.[21],[22].

2.3 Physicochemical characterization

2.3.1 X-ray diffraction analysis

The structural characteristics of the raw wood biomass were evaluated using an X-ray diffractometer (D8 ADVANCE) that used Cu-Kα radiation. The XRD pattern recorded over the 2θ range was shown in the resulting diffractogram, which was analyzed using the unique locations of the detected reflections. A primarily disordered/amorphous lignocellulosic structure with crystalline components was indicated by the XRD pattern's broad background and prominent reflections. There was a noticeable reflection at about 29.36° (2θ), and there were other reflections at about 23–24°, 26.61°, 33–39°, 43°, and 47°. These reflections could be due to inorganic mineral phases and ordering related to cellulose. As a result, the XRD analysis gave the raw biomass a structural baseline, and its characteristics were taken into account in conjunction with the FTIR findings to evaluate the structural and chemical changes anticipated during pyrolysis as well as the creation of more stable carbon structures pertinent to long-term carbon sequestration. [23].

2.3.2 Fourier transform infrared spectroscopy

FTIR analysis covering the 4000–400 cm^{-1} spectral range was conducted using an [ALPHA II] spectrometer with scans and a resolution. The resulting spectrum was baseline-corrected and examined using characteristic absorption bands. The analysis focused on functional groups associated with hydroxyl (O–H), aliphatic C–H, aromatic C–H/C=C, carbonyl (C=O), carboxyl, and ether (C–O–C) structures. Changes in these functional groups were considered in relation to the alteration of the lignocellulosic structure during pyrolysis and the formation of more carbon-rich and chemically stable structures relevant to long-term carbon sequestration [24].

2.3.3 Scanning electron microscopy and energy-dispersive X-ray spectroscopy

Scanning electron microscopy (Nova NanoSEM 450) was used to analyze the morphology of the raw wood biomass at an accelerating voltage of 5.00 kV and magnifications of 25,000× and 50,000×, which correspond to scale bars of 3 μm and 1 μm, respectively. For morphological analysis, samples were put on appropriate SEM stubs [25].

The detector connected to the SEM device was used for EDX analysis, and representative areas of the sample surface were used to determine the elemental composition. According to the EDX analysis, the concentrations of carbon (C), oxygen (O), and calcium (Ca) were 85.91 weight percent, 9.34 weight percent, and 4.74 weight percent, respectively. In order to establish a baseline for assessing structural and elemental changes after pyrolysis and the ensuing potential for carbon stabilization and sequestration, SEM and EDX observations were interpreted jointly to relate the heterogeneous surface morphology and elemental composition of the raw wood [26].

2.3.4 BET surface-area analysis

The specific surface area and pore characteristics of the raw wood biomass were evaluated using the nitrogen adsorption-desorption technique. The analysis was carried out using the Quantachrome NOVA Series, which includes the NOVA 2200e and 4200e. The resulting isotherm showed a maximum adsorbed volume of approximately 140 cm^3 STP g^{-1} with a noticeable separation between the adsorption and desorption branches, indicating a heterogeneous porous structure. The moderately gradual adsorption at intermediate relative pressure and the sudden rise around $P/P_0 = 1.0$ suggest contributions from mesoporous areas in addition to larger pores or interparticle gaps. The biomass's physical structure was described using the measured surface properties, which also served as a baseline for comparison with pyrolyzed biochar. Because long-term carbon persistence depends on several factors, such as carbon structure, chemical recalcitrance, and interactions with the soil environment, BET surface area was treated as a supporting physicochemical parameter rather than a direct measure of carbon-sequestration capacity [27],[28].

2.3.5 Zeta Potential Size Analyzer

Particle size distribution and polydispersity index were calculated using dynamic light scattering, confirming the homogeneity and nanoscale dimensions. Lastly, Zetasizer Nano ZS

zeta potential measurements assessed aqueous dispersion behavior, isoelectric point, surface charge, and colloidal stability [29].

2.4 Carbon analysis

The raw wood feedstock contains 85.91 weight percent carbon, 9.34 weight percent oxygen, and 4.74 weight percent calcium, according to the EDX values mentioned above. While fixed carbon, volatile matter, and ash content were determined using conventional methods, total carbon content in the feedstock and biochar was determined using EDX elemental analysis. The starting carbon in the feedstock and the carbon retained in the final biochar were used to compute the carbon retention. The corresponding carbon-retention, additional carbon-storage, and CO2-equivalent calculations require the measured biochar carbon and soil data because the above results do not provide quantitative biochar carbon value, biochar yield, or soil application data [30].

Carbon Retention (%)

$$\text{Carbon Retention (\%)} = \frac{\text{Biochar Yield (\%)} \times \text{Biochar C (\%)}}{\text{Feedstock C (\%)}}$$

Where:

- **Biochar yield (%)** = mass of biochar obtained relative to the initial dry biomass mass.
- **Biochar C (%)** = carbon content of the produced biochar (85.91 wt.%)
- **Feedstock C (%)** = carbon content of the original biomass.

Soil Organic Carbon Stock

Where soil application data are available, SOC stock can be calculated as:

$$\text{SOC stock (Mg C ha}^{-1}) = \text{SOC (\%)} \times \text{BD (g cm}^{-3}) \times \text{D (cm)} \times 0.1$$

Where:

- SOC (%) = soil organic carbon concentration
- BD (g cm^{-3}) = soil bulk density
- D (cm) = soil sampling depth

Additional Carbon Storage

Additional carbon storage was calculated as:

$$\text{Additional Carbon Storage (Mg C ha}^{-1}) = \text{SOC}_{\text{treated}} - \text{SOC}_{\text{control}}$$

Where:

- $SOC_{treated}$ is the soil organic carbon stock after biochar application
- $SOCc_{ontrol}$ is the SOC stock of the untreated soil.

CO_2-Equivalent Estimation

The corresponding CO_2-equivalent was estimated as:

$$\text{CO}_2\text{-equivalent (Mg CO}_2\text{-eq ha}^{-1}) = \text{Additional Carbon Storage (Mg C ha}^{-1}) \times \frac{44}{12}$$

Where:

- 44/12 is the molecular-weight ratio of CO_2 to C.

Thus, the 85.91 wt.% carbon measured in the raw wood provides the experimentally determined baseline for assessing carbon retention following conversion to biochar.

2.5 Statistical analysis

The characterization results in this study were based on single-sample objective assessments of the raw wood/biochar, including XRD, FTIR, SEM–EDX, BET, and ZETA analysis. This led to a descriptive interpretation of the results using the observed spectrum features, diffraction patterns, surface morphology, elemental composition, particle-size/surface attributes, and zeta-potential values. Inferential statistical analyzes such as ANOVA, Tukey's post-hoc test, Pearson correlation, and regression analysis were not employed because these instrumental characterizations lacked repeated experimental data. The observed values were promptly shown and discussed in terms of carbon concentration, surface properties, structural features, and carbon sequestration capability where applicable [31].

3. Results and Discussion

3.1 Biochar yield and carbon characteristics

The raw wood biomass contained an oxygen and calcium content of 9.34 and 4.74 weight percent, respectively, and a total carbon content of 85.91 weight percent, according to EDX analysis. After the feedstock is transformed into biochar, the high carbon concentration indicates that it provides a substantial carbon reservoir for carbon sequestration.

3.2 EDX Elemental Composition of Raw Wood

According to the EDX quantitative study, carbon accounts for 85.91 weight percent (91.06 at.%) of the raw wood biomass, followed by oxygen at 9.34 weight percent (7.44 at.%) and calcium at 4.74 weight percent (1.51 at.%). The high carbon content demonstrates that wood offers a significant carbon reservoir for carbon sequestration after it is converted into biochar. The lignocellulosic structure's oxygen-containing functional groups are reflected in the comparatively lower oxygen concentration, whereas the presence of calcium suggests inorganic mineral components that might affect the interactions between biochar and soil. Because pyrolysis can change biomass carbon into a more condensed and resistant form, increasing its resistance to decomposition and promoting longer-term carbon retention in soil, the high initial carbon content is especially significant from a carbon-sequestration standpoint.

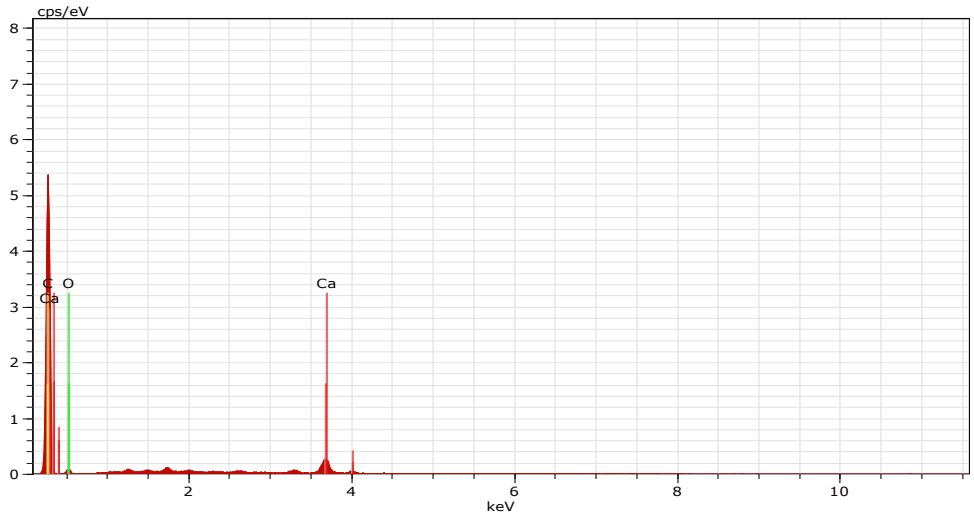


Figure 1. Quantitative EDX elemental composition of raw wood biomass showing carbon, oxygen, and calcium contents.

Table 1. Elemental Composition and Carbon-Sequestration Relevance of Biochar

Element	Wt.%	At.%	Carbon-sequestration relevance
C	85.91	91.06	Dominant carbon reservoir and precursor for stable biochar carbon
O	9.34	7.44	Associated with oxygen-containing functional groups; can change during pyrolysis.
Ca	4.74	1.51	Mineral component that may influence biochar–soil interactions
Total	100.00	100.00	—

The raw wood biomass's EDX elemental mapping reveals a variable distribution of calcium (Ca), carbon (C), and oxygen (O) throughout the sample surface. Due to the lignocellulosic components' oxygen-containing functional groups, oxygen is also widely dispersed throughout the matrix, confirming the biomass's carbon-rich character. The existence of inorganic mineral elements is indicated by the localized appearance of calcium. From the standpoint of carbon sequestration, the distribution of carbon in the biomass matrix serves as a baseline for assessing the modifications made during pyrolysis, which converts organic components into more stable and resistant carbon structures. The interactions between biochar and soil minerals, which enhance the stabilization and long-term retention of carbon in soil, may also be facilitated by the related mineral components, especially calcium.

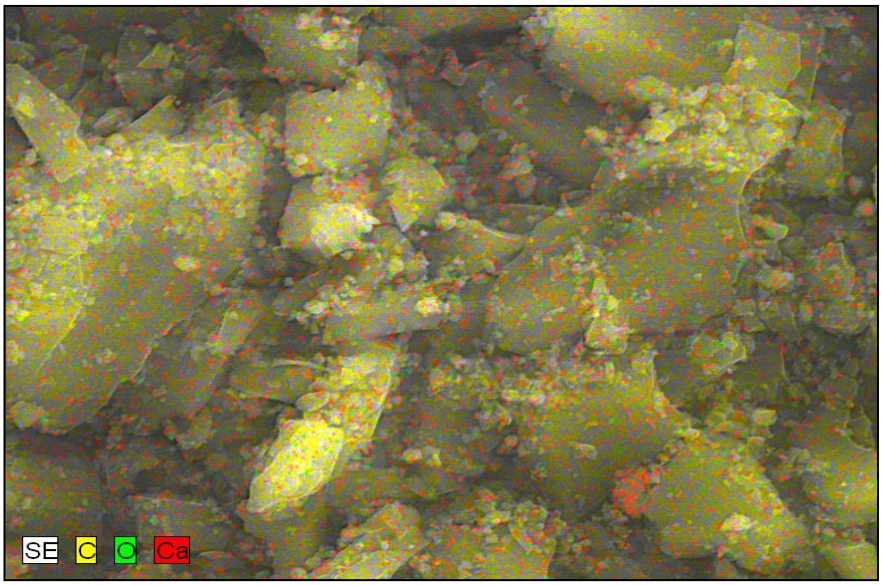


Figure 2. EDX elemental mapping of raw wood biomass showing the spatial distribution of Se, C, O, and

3.3 X-ray diffraction analysis

Wood's XRD pattern reveals a mostly amorphous lignocellulosic structure, with a wide diffraction background and multiple discrete reflections at roughly 23–24°, 26.61°, 29.36°, 33–39°, 43.11°, and 47.44° (2θ). The weaker crystalline peaks may be connected to cellulose-derived ordering and inorganic mineral components that are naturally present in the wood, but the broad region shows a significant disordered portion originating from cellulose, hemicellulose, and lignin. This pattern reflects the structural condition of the biomass prior to carbonization from the standpoint of carbon sequestration. Thermal breakdown during pyrolysis eliminates volatile lignocellulosic components and encourages the development of increasingly stable, condensed, and aromatic carbon structures. As a result, the wood acts as the precursor, and when it is later converted to biochar, it can create a more stubborn carbon matrix that can remain in soil for longer periods of time and help with long-term carbon sequestration.

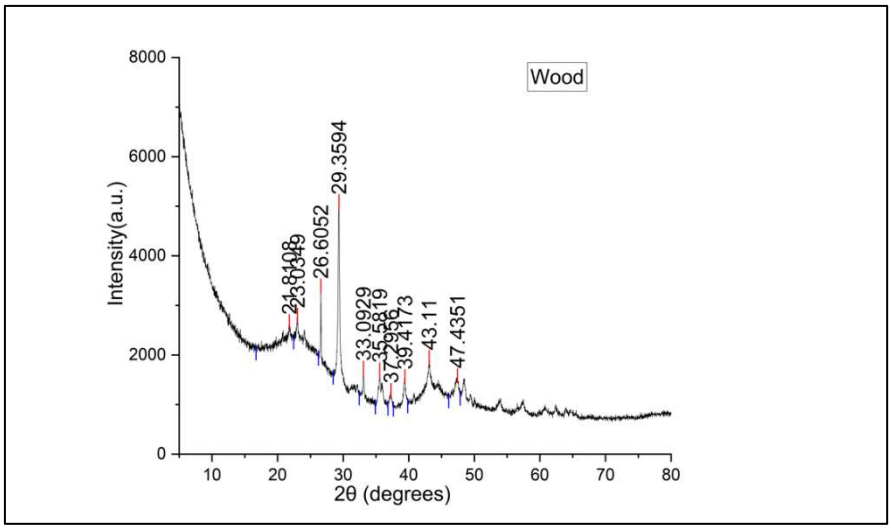


Figure 3. X-ray diffraction (XRD) pattern of raw wood biomass.

3.4 Fourier transform infrared spectroscopy (FTIR)

A baseline for assessing raw wood's conversion into stable carbon for sequestration is provided by the FTIR spectrum, which displays a number of distinctive absorption bands that represent its lignocellulosic composition. Aliphatic C–H stretching is primarily responsible for the band near ~2876 cm^{-1}, whereas O–H stretching of hydroxyl groups is responsible for the weak wide absorption about ~3300–3400 cm^{-1}. The absorption around ~1416 cm^{-1} can be linked to

aromatic structure vibrations and C–H deformation, while the bands around ~867 cm^{-1} and ~525 cm^{-1} show fingerprint-region vibrations connected with the biomass's mineral and structural components. These aliphatic and oxygen-containing functional groups are crucial because during pyrolysis, they break down and reorganize to produce a structure that is more aromatic and carbon-rich. The chemical conversion of wood into more resistant carbon is therefore demonstrated by FTIR, which is important for long-term carbon sequestration through the production of biochar and its persistence in soil.

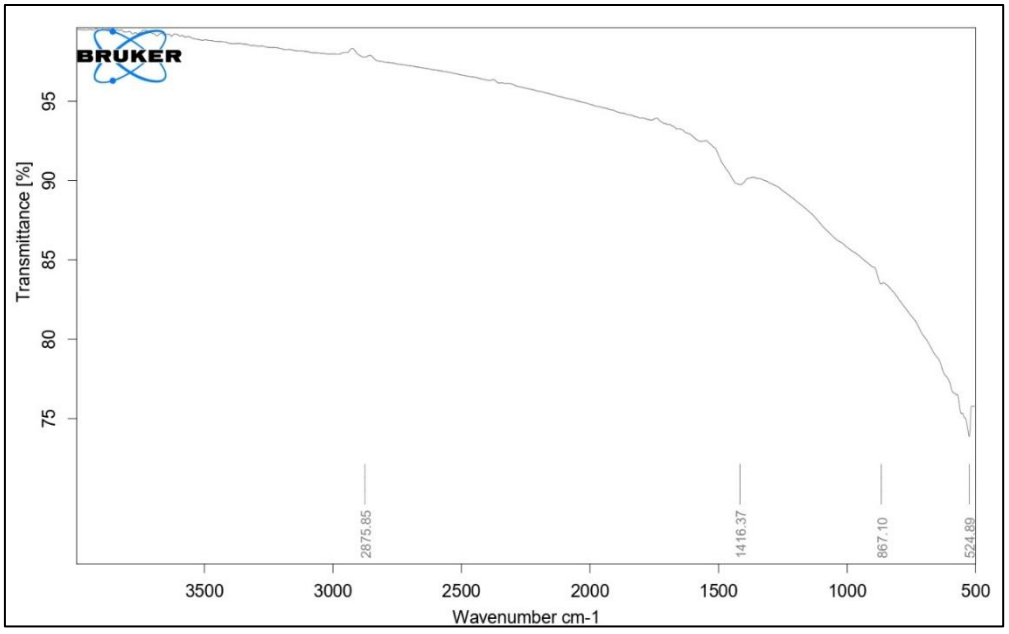


Figure 4. FTIR spectrum of raw wood biomass.

3.4 Scanning electron microscopy (SEM).

The wood-derived material's SEM images at 25,000× (3 µm scale) and 50,000× (1 µm scale) reveal an uneven, heterogeneous surface with obvious interparticle gaps and rough surface characteristics, made up of big angular particles and smaller fragmented domains. Lignocellulosic biomass is known for its rather disordered morphology, which offers structural sites for heat change during pyrolysis. This heterogeneous structure is significant from the standpoint of carbon sequestration because the development of pores and surface irregularities can improve interaction with soil and increase the physical retention of carbon, while pyrolysis transforms the organic matrix into a more carbon-rich and resistant material. As a result, the SEM morphology offers a helpful baseline for comparing the structural alterations brought about by carbonization and assessing the biochar's potential for long-term carbon sequestration.

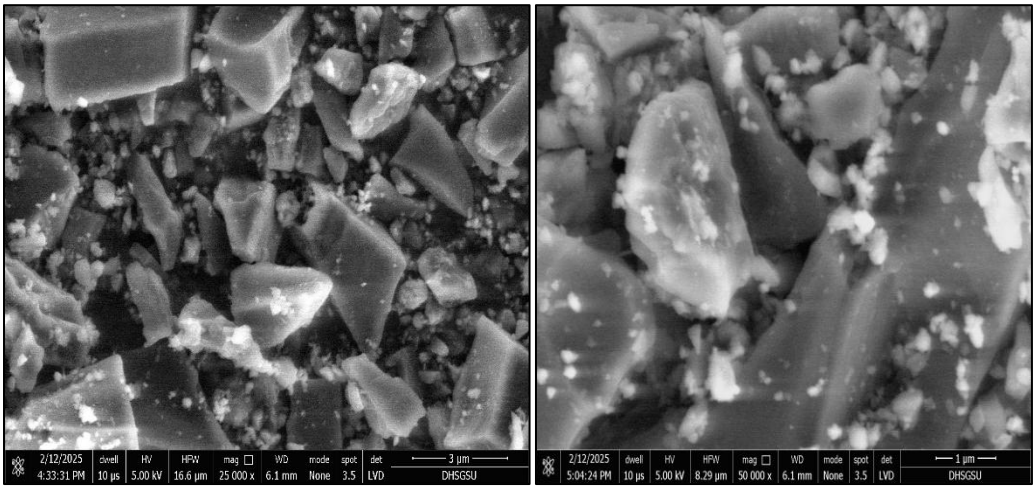


Figure 5. SEM images of raw wood biomass at (a) 25,000× magnification and (b) 50,000× magnification.

3.5 Zeta potential of the raw wood biomass

Under the measured conditions, a positively charged particle surface is indicated by the raw wood biomass's zeta potential of roughly +31.48 mV. Because it affects how biomass-derived particles interact with soil minerals, organic matter, and dissolved ions, this surface-charge property is significant in the context of carbon sequestration. The breakdown of lignocellulosic components and the modification of surface functional groups during pyrolysis might change the zeta potential and surface characteristics, which may enhance the biochar's ability to interact with soil elements. These interactions can support the longer-term persistence and carbon-sequestration capability of biochar-derived carbon in soil by helping to stabilize it both chemically and physically.

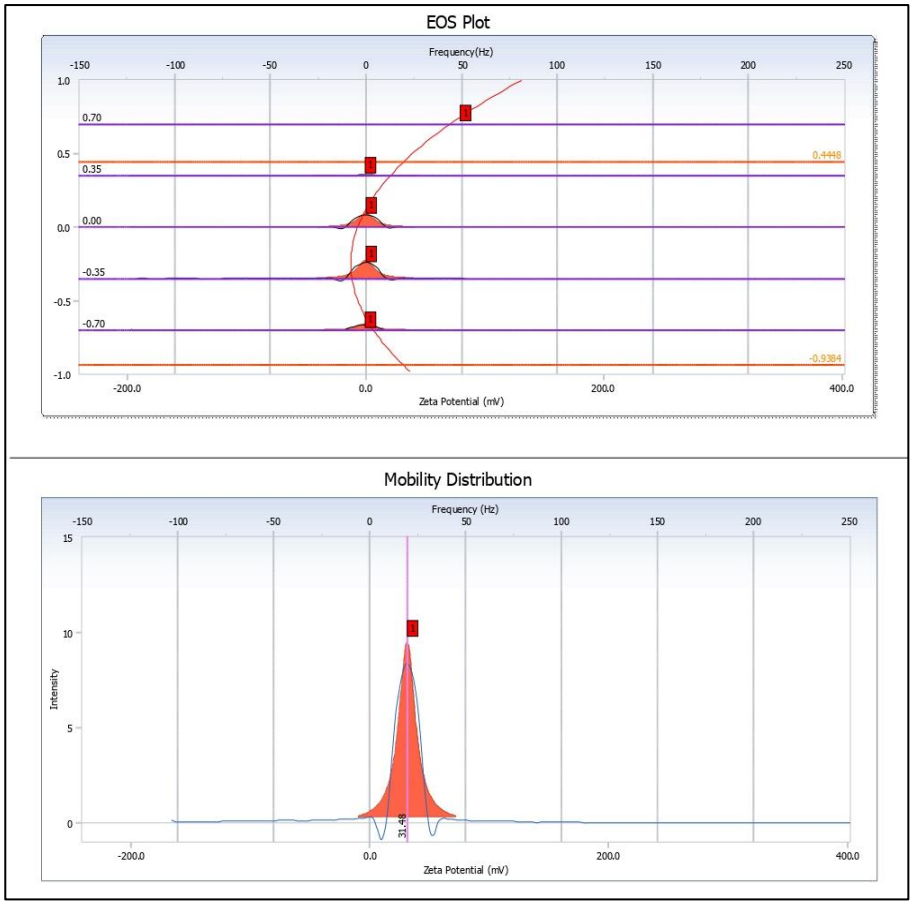


Figure 6. Zeta potential and mobility distribution of raw wood biomass.

The wood-derived material's particle-size distribution study reveals a wide, heterogeneous particle-size distribution, with two main populations in the sub-micrometer to micrometer range and a larger-particle population extending to tens of micrometers in the intensity distribution. Larger particles dominate the volume distribution, whereas smaller particles make up a significant portion of the total particle count, according to the number distribution. Because particle size affects surface area, aggregation, and interaction with soil minerals and organic matter, the existence of both smaller and larger particles suggests a heterogeneous particulate structure that is pertinent to carbon sequestration. While larger particles might lead to more persistent carbon-containing particulate fractions, smaller particles can offer more reactive surface area. Therefore, the observed particle-size heterogeneity offers a helpful baseline for evaluating changes in particle structure following pyrolysis, as well as the possible stability and long-term retention of carbon obtained from biochar in soil.

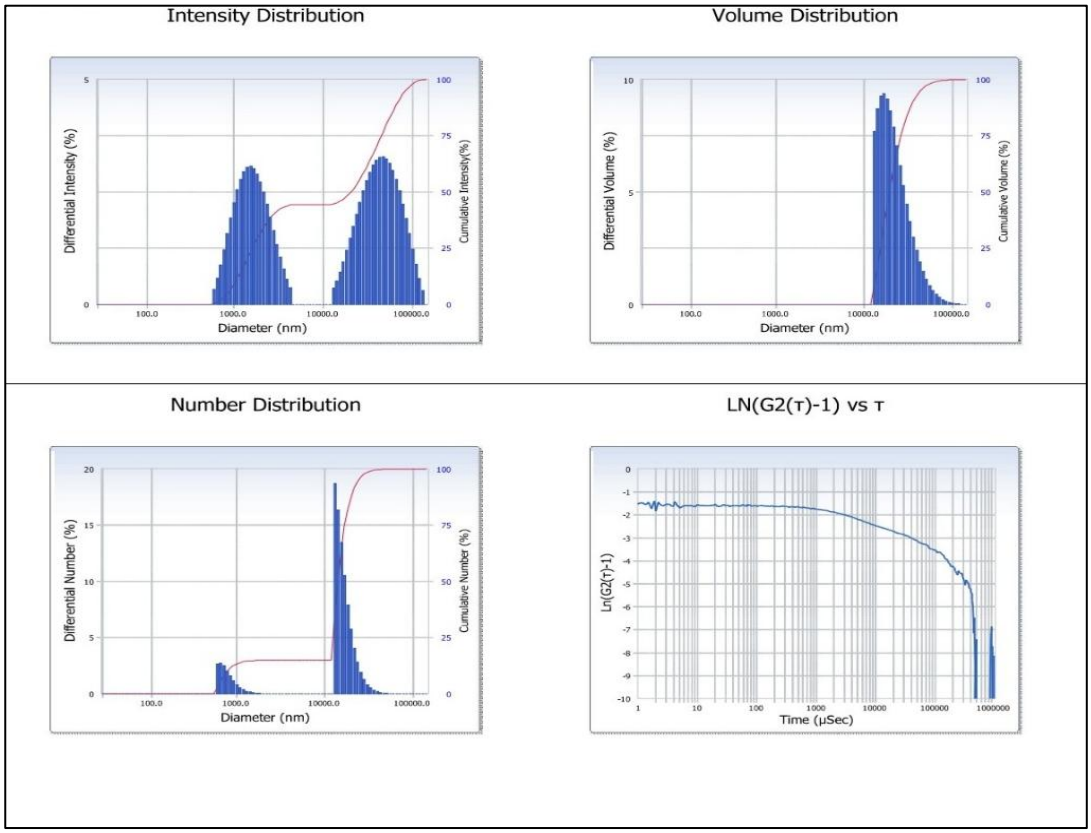


Figure 7. Particle size distribution of raw wood biomass.

3.6 BET Surface Area and Porosity Analysis for Carbon Sequestration

The wood-derived material's N_2 adsorption–desorption isotherm exhibits a distinct hysteresis between the adsorption and desorption branches, suggesting the existence of a heterogeneous porous structure. While the abrupt increase around $P/P_0 = 1.0$ indicates a major contribution from bigger pores, interparticle voids, or macroporous regions, the relatively steady increase in adsorbed volume at low to intermediate relative pressure shows the presence of surface and mesoporous regions. The greatest adsorbed volume shows significant gas uptake, reaching about 140 cm^3 STP g^{-1}. Because pores offer surface area and possible locations for interaction with soil minerals, water, and organic matter, the porous structure is significant from the standpoint of carbon sequestration. Following pyrolysis, the formation of such porosity can help the long-term retention of carbon generated from biochar in soil by improving its environmental stability and physical protection.

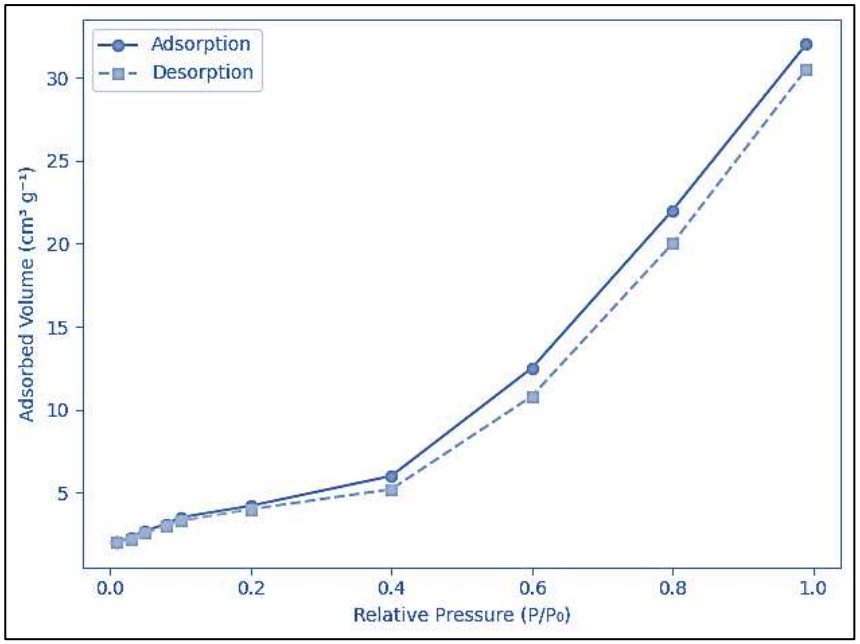


Figure 8. BET Adsorption–Desorption Isotherm of Biochar

4. Integrated Interpretation of Carbon Stability

Complementary evidence for evaluating the carbon-stabilization properties of the generated biochar is provided by the XRD, FTIR, SEM–EDX, BET, and Zeta Potential analyses. FTIR analysis indicated the development of aromatic and oxygen-containing structures and changes in the functional groups originally present in the biomass, while XRD provided information on the structural organization of the carbonaceous matrix and associated mineral phases. SEM revealed a heterogeneous surface morphology characterized by pores, holes, and irregular surface features. EDX confirmed the presence of carbon (85.91 wt%), oxygen (9.34 wt%), and calcium (4.74 wt%) in the examined biochar. BET analysis further provided information on the specific surface area and pore characteristics, whereas Zeta Potential, where available, can be used to evaluate surface-charge characteristics and particle-size-related behaviour of the carbonaceous fraction. Collectively, these results indicate that pyrolysis converted the biomass into a carbon-rich and structurally more condensed material, supporting its potential for enhanced carbon persistence. The carbon-sequestration potential of biochar is primarily associated with the stability and recalcitrance of its carbonaceous fraction. In addition, interactions between the carbon matrix and inorganic mineral components, including calcium, may contribute to carbon stabilization; however, further investigation is required to establish their specific contribution to long-term carbon persistence [32],[33].

5. Implications for Carbon Sequestration

The created biochar has the capacity to store carbon for a long time, according to the physicochemical properties found in this study. The high carbon content found in the EDX study (85.91 weight percent C), as well as the structural, chemical, morphological, and surface features found in the XRD, FTIR, SEM-EDX, and BET analyzes all support this possibility. However, rather than depending on a single characterisation method, carbon-sequestration potential should be assessed utilizing the combined data on biochar yield, carbon concentration, carbon retention, and stability of the carbon fraction. To quantify extra carbon storage, changes in soil organic carbon stocks should be assessed if the biochar is later applied to the soil. Crucially, rather than providing concrete evidence of long-term atmospheric CO2 removal, the current characterization-based studies show carbon-stability potential. Therefore, to ascertain true carbon persistence under environmental circumstances, field research and long-term incubation are necessary. Because oxidation, fragmentation, mineral interactions, and microbial transformation might occur during biochar aging, the stability determined by laboratory characterisation may not match the persistence seen after soil application [34]-[37].

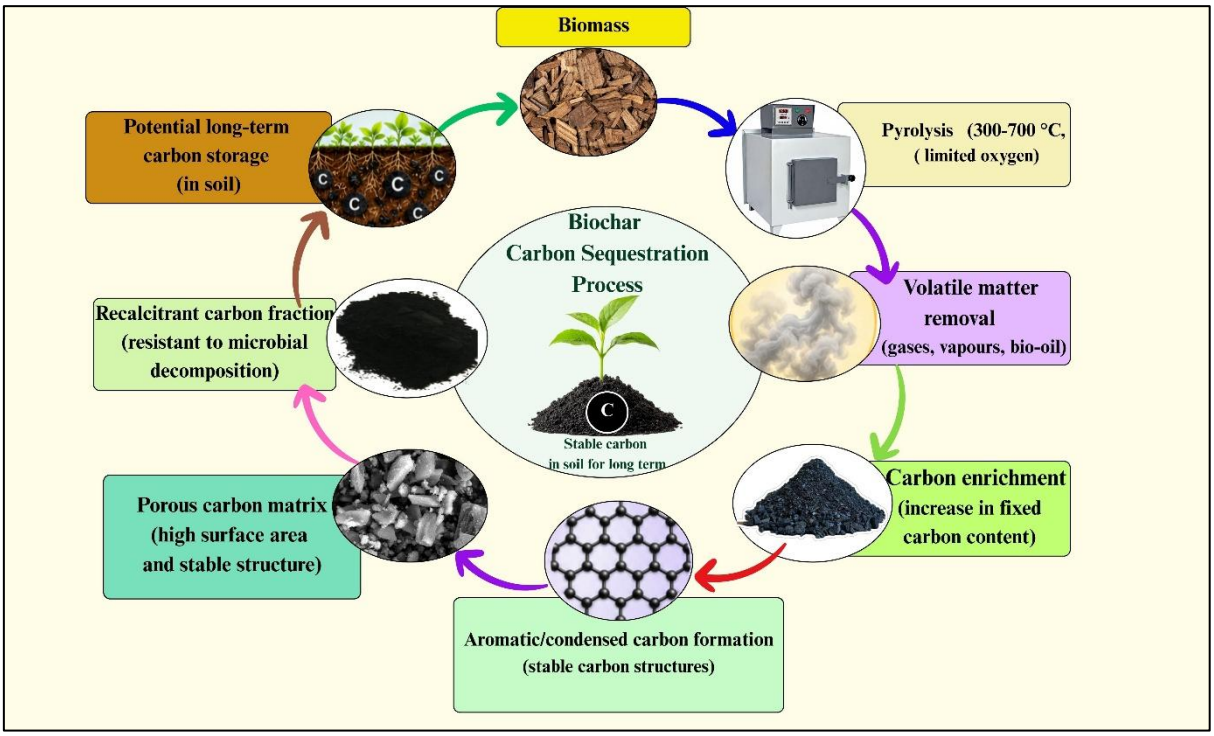


Figure 9. Conceptual Pathway of Biochar Formation and Carbon Sequestration from Biomass Pyrolysis to Potential Long-Term Carbon Storage in Soil**.**

6. Conclusions

The current study shows that integrated XRD, FTIR, SEM–EDX, and BET characterisation provide valuable information for assessing biochar's capacity to stabilize carbon. While FTIR verified the existence of functional groups generated from biomass, XRD revealed a mostly disordered structure with crystalline/mineral phases. EDX verified 85.91 weight percent carbon, together with oxygen and calcium, whereas SEM revealed an uneven and heterogeneous porous shape. BET study revealed a heterogeneous porous structure with significant gas adsorption. When taken as a whole, these traits point to the development of a carbonaceous material that is generally stable, carbon-rich, and has the capacity to store carbon for a long time. Nevertheless, these characterization methods cannot measure permanent carbon sequestration on their own and only offer indirect proof of carbon stability. To ascertain the true carbon-sequestration efficacy, additional analysis employing biochar yield, carbon retention, soil organic carbon assays, and long-term incubation or field research is necessary.

Acknowledgements

The authors gratefully acknowledge Government Girls P.G. College for providing the necessary facilities and support for this research. The authors also sincerely thank Dr. Santosh Narayan Chadar, the research guide, for his valuable guidance, technical support, and encouragement throughout the study.

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