Action Research Journal Indonesia (ARJI)
Volume 8 Number 3 Year 2026 | Pages 1070 -1084
E-ISSN : 2775-0787 | P-ISSN : 2774-9290 | DOI : 10.61227
Address : Tuesday Block No. 76 Rt/Rw 01/003 Jatitengah Village, Jatitujuh District, Majalengka Regency, West Java
e-mail : arjijournal@gmail.com
Url Web : https://journal.nahnuinisiatif.com/index.php/ARJI

Valorization of African Elemi Shell Waste Into Porous Hydrochar Via Hydrothermal Carbonization for Carbon Capture Applications

Article Information :
Articles Submitted : 2026-07-25
Articles Received : 2026-08-11
Published Articles : 2026-08-12

Calistus Princewill Odeh[1]*
Chibuzo Ndubuisi Okoye [2]
Augustine Uzodinma Madumere [3]
Sunday Chimezie Anyaora[4]

[.1,2,3,4] Nnamdi Azikiwe University, Awka, Anambra State, Nigeria

Email Correspondence * : cp.odeh@unizik.edu.ng

Keywords:
biomass, hydrochar, surface area, pore volume, capture, carbonization

Abstract: *Because of the world's rapid expansion, more biomass waste is being produced as a result of increased agricultural and industrial processing activities. It is imperative that these waste materials be transformed into a product that can stimulate the economy and create wealth. In this task, African elemi shells are hydrothermally carbonized to produce hydro-char using locally sourced biomass waste. In order to create a hydro-char of higher quality for the adsorbent, the Response Surface Method was used to design the experiment. A design expert chose the parameters based on temperature, residence time, and W-B ratio. The combination of 220 °C reaction temperature, 90 minutes' residence time, and 12 grams W-B ratio produced the hydro-char with the largest specific surface area (976.3 m2/g) and pore volume (2.25 cc/g). The combination of 180 °C reaction temperature, 30 minutes' residence time, and 8 grams' water-biomass ratio produced the hydro-char with the smallest specific surface area and pore volume (156.2 m2g-1 and 0.13 cc/g, respectively). According to the findings, the hydrochar made from HTC of African Elemi Shell at reaction temperatures of 2180C, residence times of 86 minutes, and a water-to-biomass ratio of 10.3 grams can be used as an adsorbent for CO2 capture.*

Conceptualization: all authors
Methodology: all authors
Investigation: all authors
Writing original draft preparation: all authors
Writing review and editing : all authors
Visualization: all authors

All authors have read and agreed to the published version of the manuscript.

Acknowledgments
All praise and gratitude to God for the successful completion of this article. The author expresses his gratitude to all parties involved and those who contributed to its preparation. Thanks to their constant prayers and support, this article was successfully completed.

INTRODUCTION

The conversion of industrial and agricultural biomass wastes into value-added products like hydrochar and biochar has been the subject of much research due to the growing demand for affordable and sustainable carbon materials. Global environmental issues such as increasing CO_2 emissions, climate change, and industrial pollution are major contributors to this growing interest [1]. With a variety of uses in energy-related technologies, pollution control, and carbon sequestration, biomass-derived carbons are appealing due to their renewable nature, economic viability, and environmental friendliness [2]. The type of biomass feedstock has a significant impact on the characteristics and functionality of biochar and hydrochar because carbon-rich materials like forestry wastes, animal byproducts, urban biomass, and agricultural residues typically produce higher-quality carbon products [3]. The most popular thermochemical conversion processes for turning biomass into useful carbonaceous materials are pyrolysis and hydrothermal carbonization (HTC) [4]. HTC is especially useful for wet biomass because it doesn't require energy-intensive drying and can function in an aqueous environment at relatively mild temperatures (180–260 °C and 2–6 MPa) [5,6]. Hydrochar is produced during HTC, along with bio-oil and other trace gaseous products, by processes like hydrolysis, dehydration, decarboxylation, and condensation [7]. Hydrochar is a promising material for CO_2 adsorption and carbon capture applications because it usually retains a sizable portion of the initial biomass carbon and energy content [8–10]. Processing parameters such as reaction temperature, residence time, water-to-biomass ratio, feedstock type, and catalyst presence, which together control yield, surface area, and pore structure, have a significant impact on its adsorption performance [11,12]. Even though pristine hydrochar frequently has low surface area and microporosity, these issues can be resolved by optimizing the process or by using post-treatment and activation techniques [13]. Nigeria, Ghana, Cameroon, and other parts of West and Central Africa are home to the tropical tree known as the African elemi (Canarium schweinfurthii) [14]. Locally referred to as "Ube" or "Atili," its fruits are eaten for their edible pulp, producing copious amounts of hard, carbon-rich shells that are usually thrown away as waste [15]. Considering their high carbon content and large availability, African elemi shells are very promising but largely underexploited source of hydrochar produced by the hydrothermal carbonization process (HTC). The valorization of this specific biomass is not only highly relevant in helping to alleviate the environmental burden usually associated with the disposal of agricultural waste, but also greatly contributes to overall strategies for sustainable carbon capture and climate change alleviation. In the present comprehensive study, hydrochar was produced from the African elemi shells via HTCW process and had its yield as well as textural properties (pore structure mostly) affected by a number of key parameters that were systematically and painstakingly evaluated. Additionally, the adsorption ability of the resultant hydrochar towards carbon dioxide (CO_2) is systematically accessed, which will supply valuable information for the sustainable use of local biomass resources in effective environmental management.

Figure 1. African Elemi (*Canarium schweinfurthii*)

MATERIALS AND METHODS

We collected African elemi shells (*Canarium schweinfurthii)* from agricultural waste sites in Aku, Igbo Etiti Local Government Area, Enugu State, Nigeria. First, we cleaned the raw shells to get rid of dirt and any leftover material. After that, we left out in the sun for three days to dry. Once they dried out, we broke them up with a hammer. To remove any lingering pigments or impurities, we soaked the shells in a sodium hydroxide solution (4 g/dm^3) for another three days. Then we rinsed them and let them dry again under the sun for 72 hours to cut down the moisture. After all that, we used an industrial ball mill to grind the shells into powder and sieved them until we got a consistent particle size of 300 µm. We set aside 50 grams of this prepared sample to use for hydrochar synthesis.

Research Design for HTC of Hydro-Char

1. Production of hydrochar from African elemi shell

Hydrochar was produced from African elemi shells according to the defined experimental conditions. A measured amount (50 g) of the prepared biomass was mixed with water in a sealed hydrothermal reactor and heated to the desired temperature for a predetermined time. After cooling, the solid and liquid products were separated, and the recovered hydrochar was washed and sun-dried for 72 hours. The synthesis was repeated at different temperatures and reaction times under a constant heating rate, as illustrated in Figure 2.

2. Research Design for Hydro-Char Production

Hydrothermal carbonization (HTC) experiments were planned and optimized using Response Surface Methodology (RSM) with a Central Composite Design (CCD). Design Expert software (Version 13) was employed to assess the effects of reaction temperature, reaction time, and water-to-biomass ratio on key responses, including char yield, oil yield, surface area, pore volume, and pore size. Fifteen experimental runs were conducted using different combinations of these variables.

Table 1.
Design Factors and Their Maximum and Minimum Values for HTC

Factor	Name of factor	Unit	minimum level	maximum level
A	Reaction Temperature	^{o}C	180.00	220.00
B	W-B Ratio	g	8.00	12.00
C	Reaction Time	min	30.00	90.00

Research Design Response Analysis

To figure out the texture of the hydrochars, we used nitrogen adsorption–desorption with a Gemini Surface Area Analyzer (Micromeritics, USA), following the BET method [16-19]. First, we took about 0.15 grams of each sample and vacuum-degassed them at 250 °C. That step gets rid of any moisture or gas trapped inside. Then, we ran the measurements at liquid nitrogen temperature. We pulled specific surface area, pore volume, and pore size data from the results, using the BET and BJH models. For BET, we focused on a relative pressure range of 0 to 0.38. The BJH model helped us look at mesopore distribution, especially in the 2-50 nm range. Out of all the samples, we picked the hydrochar with the largest surface area and the best pore structure as the top choice for CO_2 adsorption.

RESULT AND DISCUSSION

Analysis of the Results

The hydrochar yield for each experiment was measured using a digital balance and expressed as a weight percentage relative to the initial biomass mass. Yield calculations were carried out using standard equations commonly applied in hydrothermal carbonization (HTC) studies, as presented below.

$$\%\, Yield_{HC} = \frac{Mass\ of\ hydro{-}char}{Mass\ of\ Biomass} \times 100$$

$$\%\, Yield_{BO} = \frac{Mass\ of\ Bio{-}Oil}{Mass\ of\ Biomass} \times 100$$

$$\%\, Yield_{gas\&water} = 100\% - \%Yield_{BO} - \%Yield_{HC}$$

Where $\%Yield_{HC}, \%Yield_{BO}, \%Yield_{gas\ \&\ water}$

Table 2.
HTC Research Design Factors and Responses

std	Reaction Temperature (°C)	Residence Time (min)	W-B Ratio (g)	Surface Area (m^2/g)	Pore size (nm)	Pore Volume (cc/g)
1	180	30	8	156.2	1.58	0.13
2	220	30	8	527.6	2.13	0.26
3	180	90	8	264.1	1.83	0.15
4	220	90	8	857.6	2.22	0.30
5	180	30	12	226.2	1.62	0.14
6	220	30	12	606.0	2.36	0.28
7	180	90	12	295.3	1.90	0.15
8	220	90	12	976.3	2.25	0.32
9	180	60	10	212.6	1.78	0.14
10	220	60	10	615.4	2.26	0.29
11	200	30	10	417.0	2.04	0.16
12	200	90	12	736.5	2.21	0.24
13	200	30	8	328.7	1.96	0.15
14	200	60	12	562.8	2.16	0.20
15	200	60	10	507.0	2.10	0.19

Hydrochar Characterization Techniques

a. Elemental Analysis

Elemental analysis of the hydrochar was performed to assess its chemical composition. Nitrogen was determined by the Kjeldahl method, while carbon, hydrogen, and sulfur were analyzed using a CHNS analyzer (LECO CHNS 628, ASTM D5373). Oxygen content was calculated by difference, and H/C and O/C ratios were derived to assess carbonization. Inorganic elements were further identified using EDXRF (ARL QUANT'X Analyzer).

b. Moisture Content of the Samples

Moisture content was determined by drying finely ground samples in a pre-weighed stainless-steel container at 105 °C using a Memmert oven. The samples were cooled to room temperature and reweighed, and the heating–cooling cycle was repeated until a constant mass was achieved. All measurements were performed in replicates, and the average constant weight was used for analysis.

$$\text{Moisture content (\%)} = \frac{\text{Wi}-\text{Wf}}{\text{Wi}} \times 100$$

Where W_i = initial mass of the sample, W_f = final mass of the sample after drying.

c. Volatile Matter of the samples

Volatile matter content was evaluated using the Meynell method. Samples dried during moisture analysis were first heated at 280 °C for 2 hours to remove volatile components, followed by further heating at 450 °C for 2 hours to complete oxidation and ash formation. After cooling, the remaining mass was measured and used to calculate the volatile matter content.

$$\text{Volatile Matter} = W_{\text{initial}} - W_{\text{after heating}}$$

$$\%\ \text{Volatile Matter} = \frac{\text{Wrd}-\text{Wds}}{\text{Wst}} \times 100$$

Where W_{rd} = mass due to removal of the volatile matter, W_{ds} = mass of dry sample after heating, W_{st} =mass of dry sample collected

d. **Ash Content of the samples**.

One gram of each dried sample was heated in a furnace at 630°C for approximately one hour. Following heating, the materials were cooled until they reached room temperature within a desiccator and then weighed. This procedure was conducted for all samples, and the average weight was taken as the final ash content

$$\text{Ash content (\%)} = \frac{\text{Wa}}{\text{Wi}} \times 100$$

Where, Wa = mass of the ash, Wi = initial mass of dried sample.

e. Fixed Carbon Content of the samples

The fixed carbon content of the sample was calculated with the following equation. Fixed carbon represents the solid carbon residue remaining in the biomass after the release of volatile matter during devolatilization. [17]:

$$\text{Fixed carbon content (\%)} = 100\% - (\%\text{AC} - \%\text{VM} - \%\text{MC})$$

Where, AC = Ash content, VM = Volatile Matter, MC = Moisture Content.

f. H/C and O/C Ratio

The carbon, hydrogen, and oxygen contents from the samples were determined through CHNSO analysis. These values were subsequently used for determining the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) molar ratios for the African Elemi Shell, hydrochar, and activated hydrochar samples. The calculations were carried out following equations (8) and (9) as outlined by [17]:

$$H/C = \frac{\text{Percentage Weight of Hydrogen} \Big/ \text{Molar Weight of Hydrogen}}{\text{Percentage Weight of Carbon} \Big/ \text{Molar Weight of Carbon}}$$

$$O/C = \frac{\text{Percentage Weight of Oxygen} \Big/ \text{Molar Weight of Oxygen}}{\text{Percentage Weight of Carbon} \Big/ \text{Molar Weight of Carbon}}$$

Results of the experiments and Discussion

1. Result of the Hydr-ochar Production

Figure 3 shows some hydrochar samples, while Table 2 summarizes the production results. The highest surface area (976.3 m^2/g) and pore volume (0.32 cc/g) were obtained at 220 °C, 90 minutes, and 12 g of water, whereas the lowest (156.2 m^2/g and 0.13 cc/g) occurred at 180 °C, 30 minutes, and 8 g of water.

2. Result of the variables on surface area

a. Result of reaction temperature & residence time with specific surface area

Higher temperatures and longer reaction times markedly increase the hydrochar's surface area. Temperature has the greatest effect on yield and structural properties. As shown in Figure 4(a), higher temperature and longer duration enhance surface area due to molecular breakdown and reorganization. The contour plot in Figure 4(b) shows the maximum surface area (800 m^2/g) at 218 °C and 86 minutes, and the minimum (200 m^2/g) at 184 °C and 40 minutes. Extended reaction times aid thermal decomposition, remove volatiles, and enhance porosity, improving CO_2 adsorption capacity.

b. Result of temperature and W-B ratio with surface area

Figure 5 shows the combined effect of temperature and water-to-biomass (W–B) ratio on hydrochar surface area. As seen in Figure 5(a), temperature strongly affects surface area, while the W–B ratio has minimal influence. At higher temperatures, pore development and aromatic structure expansion enhance surface area [13]. The contour plot in Figure 5(b) shows the smallest surface area (400 m^2/g) at 180 °C and 9.8 g W–B ratio, and the largest (800 m^2/g) at 216 °C and 10.3 g W–B ratio. Thus, rising temperature markedly improves surface area, consistent with earlier studies [20].

c. Result of residence time and W-B ratio with surface area

Figure 6 lays out how both residence time and the water-to-biomass (W-B) ratio shape the surface area of hydrochar. They each play a decent role, but neither one completely takes over. If you look at Figure 6(b), you see the lowest surface area 100 m^2/g shows up at 33

minutes with a W-B ratio of 8.5 g. On the other hand, when the process runs for 90 minutes and the W-B ratio hits 11.8 g, surface area jumps up to 400 m^2/g.

3. Effect of the factors on Pore Volume

a. Result of temperature and residence time with Pore Volume

Take a look at Figures 7(a) and 7(b), which lay out how both temperature and residence time affect hydrochar pore volume during HTC. Temperature really takes the lead here, shaping the pore structure much more than how long the process runs. As the temperature goes up, so does the pore volume. You see the lowest pore volume, about 0.15 m^3, at 180 °C after 60 minutes. Push the temperature to 213 °C and wait 62 minutes, and you get the highest value, 0.25 m^3. These findings back up what earlier studies found: temperature is the main player when it comes to making a better hydrochar pore structure [21] [22] [23].

b. Result of temperature and W-B ratio with Pore Volume

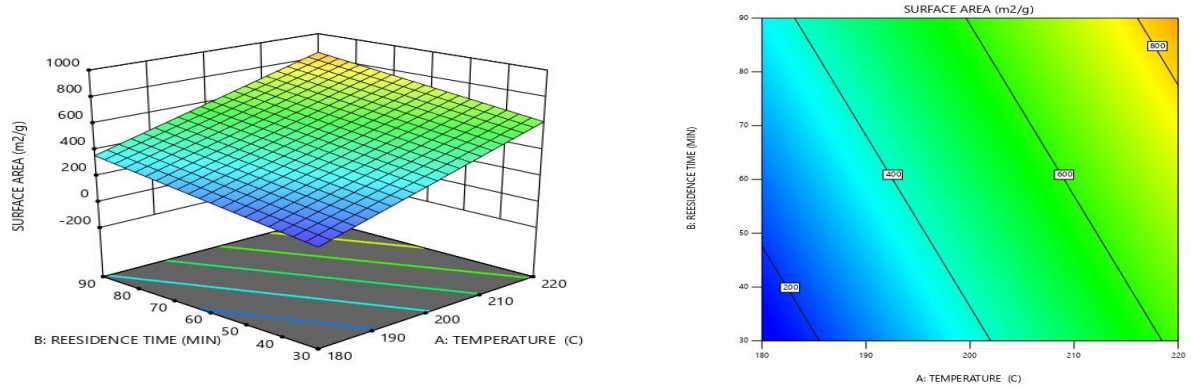
Take a look at Figure 8. It lays out how temperature and the water-to-biomass (W-B) ratio affect the pore volume in hydrochar. In Figure 8(a), temperature stands out as having a much bigger influence than the W-B ratio. When you turn up the heat, pore volume goes up too [24]. Moving to Figure 8(b), the contour plot makes it pretty clear: you get the highest pore volume, about 0.25 m^3, at 213 °C and a W-B ratio of 10.1. On the flip side, the lowest value, around 0.15 m^3, pops up at 185 °C and 10. This lines up with what Lehmann and colleagues found in 2015; they pointed out that temperature really drives pore formation [25].

c. Results of residence time and W-B ratio with Pore Volume

Figure 9 shows the combined effect of residence time and water-to-biomass (W-B) ratio on hydrochar pore volume, with temperature held constant. The interaction has only a slight impact on pore development. As seen in Figure 9(a), pore volume increases slightly with longer residence times. The contour plot in Figure 9(b) indicates the lowest pore volume (0.11 m^3) at 8.6 g W-B ratio and 34 minutes, and the highest (0.15 m^3) at 10.6 g and 84 minutes [26].

(a) (b)

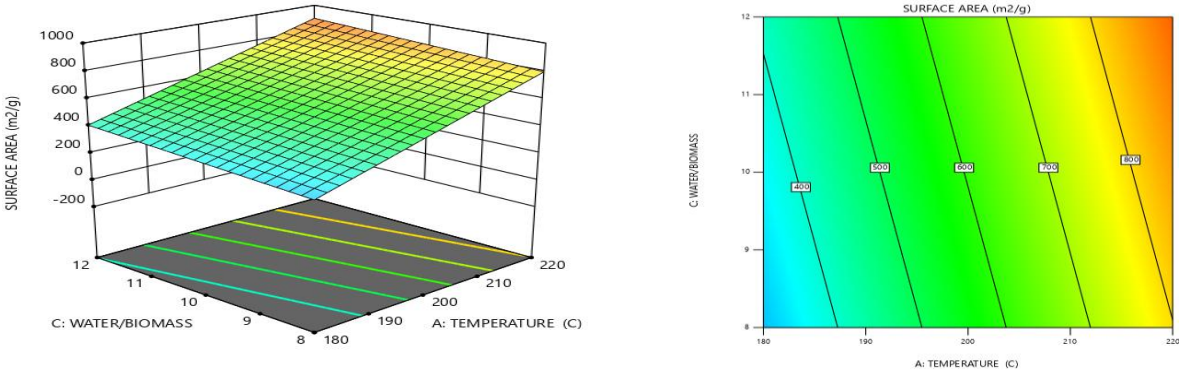
Figure 3.
(a) powder African Elemi shell and (b) African Elemi shell hydrochar samples.



(a) (b)

Figure 4.

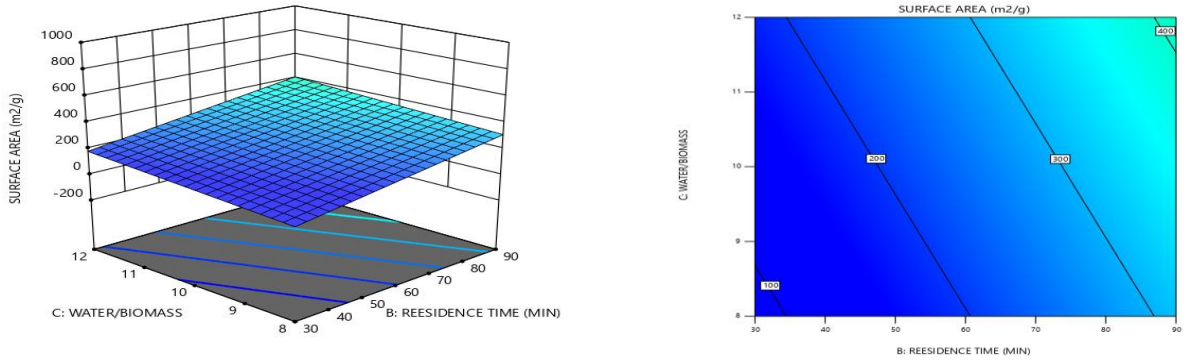
(a) response surface diagram and (b) profile plot of reaction temperature and residence time on the surface area of char



(a) *(b)*

Figure 5.

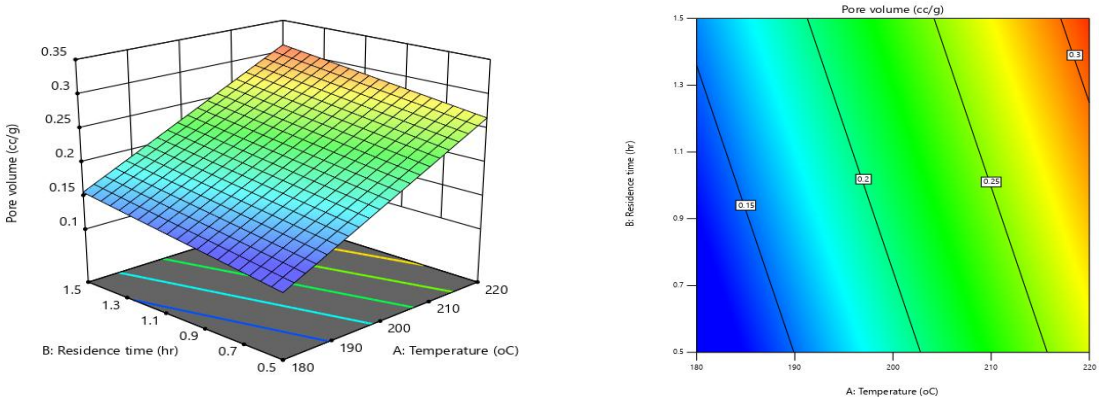
(a) response surface diagram and (b) profile plot of reaction temperature and water-biomass ratio on the surface area



(a) *(b)*

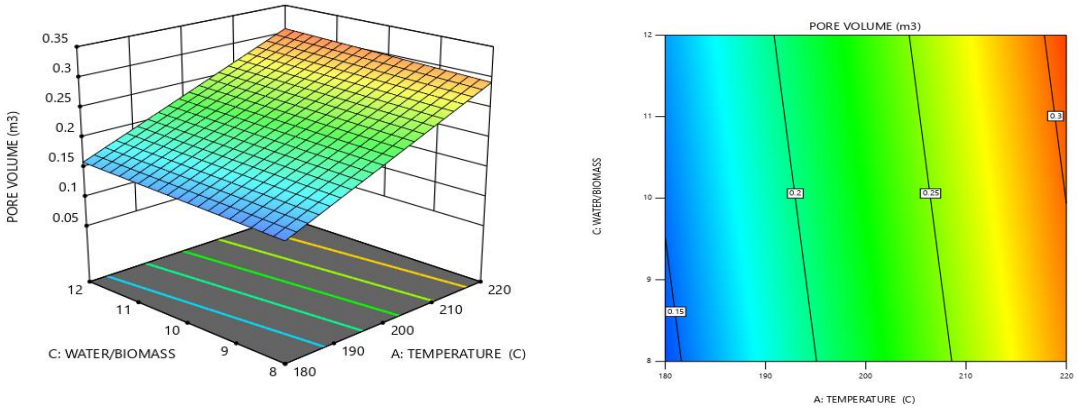
Figure 6.

(a) response surface diagram and (b) profile plot of residence time and water-biomass ratio on surface area



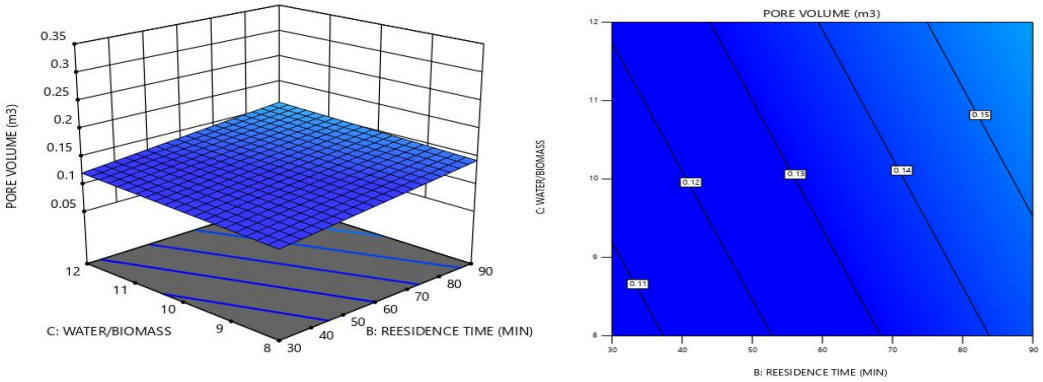
(a) *(b)*

Figure 7.
(a) response surface diagram and (b) profile plot of temperature and residence time on the pore volume



(a) (b)

Figure 8.
(a) response surface diagram and (b) profile plot of temperature and water-biomass ratio on the pore volume



(a) (b)

Figure 9.
(a) response surface diagram and (b) profile plot of residence time and water-biomass ratio on the pore volume

4. Characterization of AES and produced hydrochar

a. Comparative Analysis of Ultimate and Proximate Results

Ultimate and proximate analyses were conducted on the African fan palm shell (AES) and its hydrochar (AESH). The ultimate analysis determined elemental composition (C, H, N, S, O) and atomic ratios (H/C, O/C), while the proximate analysis measured moisture, ash, volatile matter, and fixed carbon. The results are summarized in Figure 10.

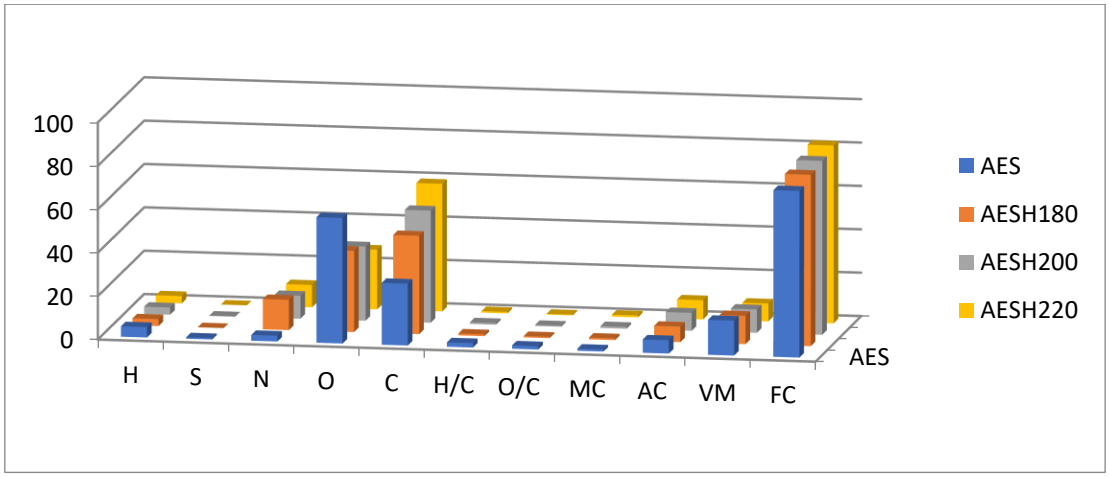


Figure 10. Comparison of the samples Ultimate and Proximate Analysis

b. Ultimate Analysis

The ultimate analysis reveals the elemental composition of the samples (C, H, N, S, and O). AESH220 (90 minutes) shows the highest carbon content, while the raw AES has the lowest. The rise in carbon content at higher temperatures is a result of dehydration and polymerization during hydrothermal carbonization, producing a carbon-rich material. In contrast, oxygen content decreases with increasing temperature, with raw AES showing the highest level.

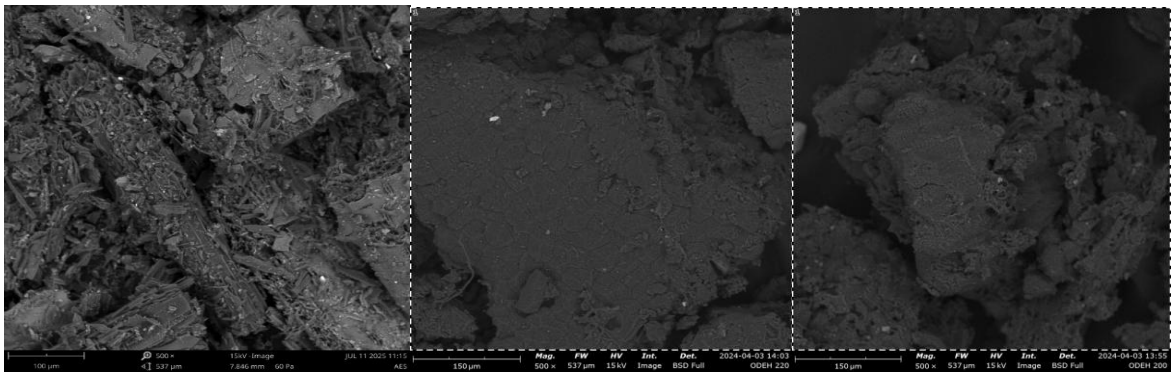
c. Proximate Analysis

Table 3 and Figure 10 present the proximate and ultimate analysis results. The bar chart compares moisture content (MC), ash content (AC), volatile matter (VM), and fixed carbon (FC) across samples. Moisture content is highest in the raw material, decreases during carbonization, and slightly rises at higher HTC temperatures. Ash content increases with temperature, while volatile matter decreases, indicating reduced carbon loss and effective carbon retention in the hydrochar during HTC.

5. Surface morphologies and textural characterization

The SEM images of raw African Elemi Shell (AES) and the hydrochars made at 180 °C and 220 °C (see Figures 11a-c) tell a pretty clear story. You get these porous, rough, and fibrous surfaces just what you'd expect from carbon materials. The raw AES looks fractured and fibrous, almost like flakes. When you bump the temperature up to 220 °C (AESH220), the structure gets a dense core with broken edges. At 180 °C (AESH180), it turns into this porous clump with finer bits scattered around, which points to a partial reaction. Then there's the EDS data (Table 4). Carbon really takes over as the temperature goes up, 54.79% in raw AES, then jumping to 85.27% at 180 °C and all the way to 88.27% at 220 °C. That's solid evidence that the material carbonizes more at higher temperatures. Nitrogen, on the other hand, drops fast: it

starts at 42.30% and drops to 14.19% at 180 °C, then down to 10.88% at 220 °C. You also start spotting trace elements like sodium, iron, and magnesium, mostly in the 220 °C sample. Most of the other minor elements from the raw biomass end up leaching out into the process liquid.



(a) (b) (c)

Figure 11. Comparison of the samples' SEM at 220 ºC and 180 ºC

a. FTIR analysis of AESH

The FTIR spectrum in Figure 13 shows some important functional groups popping up in the hydrochar. You can see a medium band at 3347.37 cm^{-1} that's the N-H stretch from primary amines, which ties back to dehydration reactions. This fits with the lower H/C and O/C ratios compared to the original biomass [27]. There's another peak at 2087.13 cm^{-1}. That one points to C≡C stretching in mono-substituted alkynes, which show up after decarboxylation and other changes during HTC [28,29]. Then, at 1636.17 cm^{-1}, you get N-H bending, hinting at polymer breakdown and the formation of more aliphatic structures [30]. So, the FTIR data really confirms you've got alcohols, alkenes, alkynes, and amines in the mix. All these changes show how HTC reshapes the material, making the hydrochar better for things like carbon capture or improving soil.

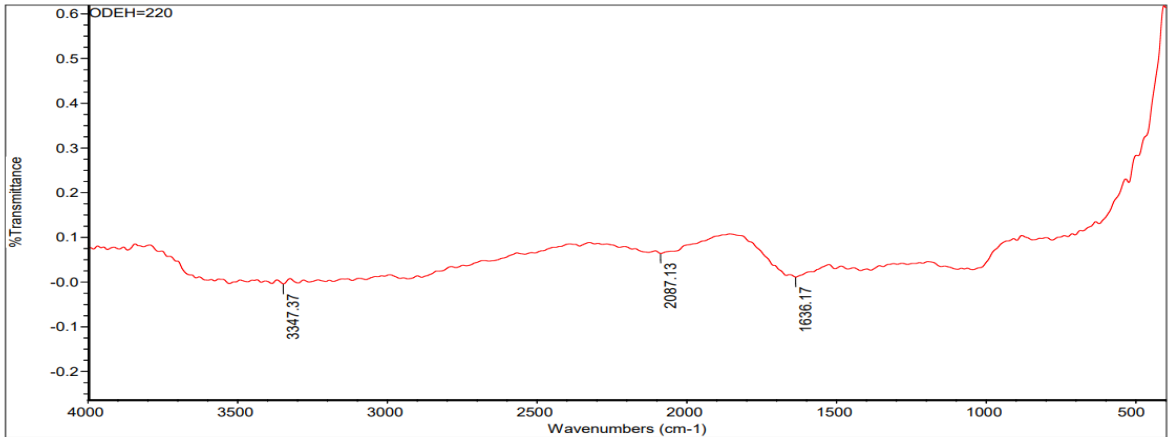


Figure 12. FTIR spectra of AESH.

b. Thermogravimetric analyses of AESH

Take a look at Figures 14a and 14b they lay out the TGA/DTA results for AES and AESH. Right away, the TGA curves show a small weight drop, just 2-3%, which comes from moisture leaving the samples. The real action happens between 300 and 500°C, where most of the

material breaks down. AES goes through a single-phase degradation, peaking at 400°C. AESH, on the other hand, breaks down in two steps, between 330 and 350°C. After all's said and done, AES leaves behind 26% residue, while AESH's residue is just 13.6%. So, AES packs in more inorganic material, while AESH shows more of the organics breaking down. The DTA curves back this up: AES degrades in one go, but AESH takes a multi-step path [31].

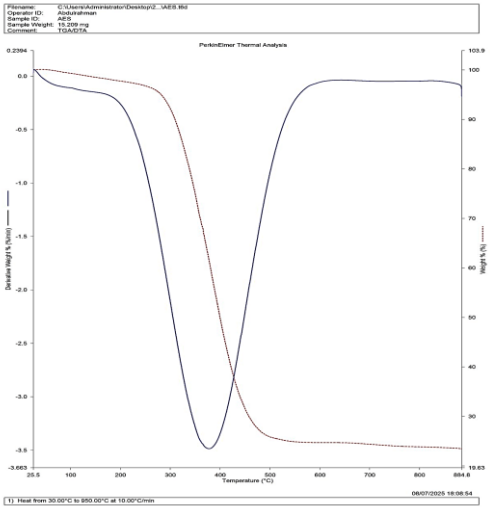


Figure 14a. TGA/DTA curve of AES

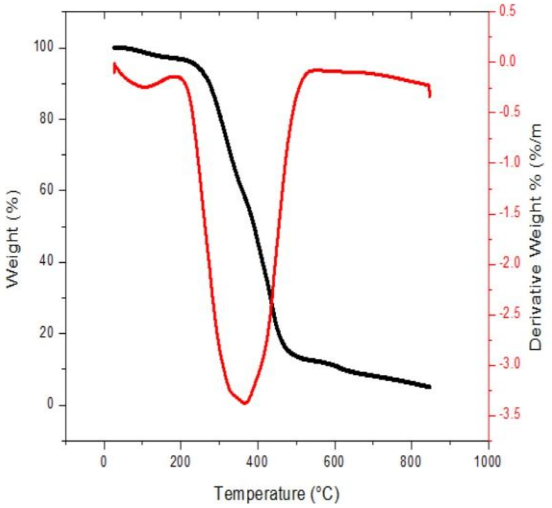


Figure 14b. TGA/DTA curve of AESH.

Conclusion

This study looks at how African Elemi Shell (AES), which usually gets tossed out as agricultural waste, can turn into something valuable porous hydrochar and biofuel using hydrothermal carbonization (HTC). Instead of just adding to the trash pile, AES gets a new life as a carbon-rich material that actually grabs onto CO_2, which is great news for the environment. The hydrochar that comes out of this process isn't just any old carbon it has a high surface area, lots of little pores, and special groups like methyl amine that help it capture even more CO_2. Here's how the team did it: they ran the process in a stainless-steel autoclave (tiny, about 0.001 cubic meters) at some serious heat and pressure 500°C and 240 bars. But the sweet spot turned out to be 220°C for 65 minutes. That's when they got the best mix of surface area and pore structure. To really nail down what they'd made, they used SEM-EDS, TGA/DTA, and both proximate and ultimate analyses. The results? This hydrochar acts a lot like coal, but with extra benefits. Bottom line: AES isn't just waste. It's a solid renewable feedstock for making sustainable carbon materials that work in energy and environmental tech.

Reference

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Arias-Navarro, C. (2019). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global change biology*.

Liu, W., G. Wang, M. Yu, H. Chen, Y. Jiang, M. Yang, & Y. Shi (2020). *Projecting the future vegetation-climate system over East Asia and its RCP-dependence*. Climate Dynamics**,** 55(9), 2725–2742. DOI: 10.1007/s00382-020-05411-2

Zhang, Y., Jin, Z., & Sikand, M. (2021). *The top-of-atmosphere, surface and atmospheric cloud radiative kernels based on ISCCP-H datasets: Method and evaluation*. *Journal of*

Geophysical Research: Atmospheres, 126(24), e2021JD035053. DOI: 10.1029/2021JD035053

Chen, W.T., Zhang, Y., Lee, T.H., et al. (2018). *Renewable diesel blendstocks produced by hydrothermal liquefaction of wet biowaste.* Nature Sustainability, 1, 702-710. DOI: 10.1038/s41893-018-0172-3

Goel, C., Mohan, S., & Dinesha, P. (2021). *CO_2 capture by adsorption on biomass-derived activated char: A review.* Science of the Total Environment, 798, 149296. DOI: 10.1016/j.scitotenv.2021.149296.

Li, Z., Yi, W., Li, Z., Tian, C., Fu, P., Zhang, Y., Zhou, L., & Teng, J. (2020). *Preparation of Solid Fuel Hydrochar over Hydrothermal Carbonization of Red Jujube Branch.* Energies, 13(2), 480. DOI: 10.3390/en13020480**.**

Wang, Y.-J., Yu, Y., Huang, H.-J., Yu, C.-L., Fang, H.-S., Zhou, C.-H., Yin, X., Chen, W.-H., & Guo, X.-C. (2022). *Efficient conversion of sewage sludge into hydrochar by microwave-assisted hydrothermal carbonization.* Science of The Total Environment**,** 803, 149874. DOI: 10.1016/j.scitotenv.2021.149874**.**

Fang, J., Gao, B., Chen, J., & Zimmerman, A. R. (2019). Hydrothermal carbonization for valorizing waste biomass: Role of feedstock properties and reaction conditions on hydrochar structure and adsorption performance. *Bioresource Technology*, 292, 121974. https://doi.org/10.1016/j.biortech.2019.121974

Kambo, H.S.; Dutta, A. Comparative evaluation of torrefaction and hydrothermal carbonization of lignocellulosic biomass for the production of solid biofuel. Energy Convers. Manag. 2015, 105, 746–755.

Libra, J.A., Ro, K.S., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.-M., Fuhner, C., Bens, O., Kern, J., Emmerich, K.-H., 2011. Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. Biofuels 2, 89–124.

M. Toufiq Reza, Janet Andert, Benjamin Herklotz, **Daniela Busch** Review Article: Hydrothermal Carbonization of Biomass for Energy and Crop Production February 2014Applied Bioenergy 1(1) DOI:10.2478/apbi-2014-0001

Wang, W., Chen, W.-H., & Jang, M.-F. (2020). Characterization of Hydrochar Produced by Hydrothermal Carbonization of Organic Sludge. *Future Cities and Environment*, 6(1), 13, 1-10. https://doi.org/10.5334/fce.102

Okoro, I. C., Ugochukwu, G. C., & Ezeokonkwo, M. A. (2017). Proximate and phytochemical composition of *Canarium schweinfurthii* (African Elemi) pulp and seed. *International Journal of Scientific & Engineering Research*, 8(8), 1504–1508.

Adewale, A. A., Olawale, O., & Akinwale, A. S. (2019). Nutritional and phytochemical evaluation of African Elemi (*Canarium schweinfurthii*) fruit pulp and seed oil. *Journal of Applied Sciences and Environmental Management*, 23(3), 501–507. https://doi.org/10.4314/jasem.v23i3.16

Odeh, C. P., Mgbemena, C. O., Oreko, B. U., & Mgbemena, C. E. (2025). *Impact of processing parameters on the hydrothermal carbonisation of African Elemi Shell*. Journal of Umm Al-Qura University for Engineering & Architecture. https://doi.org/10.1007/s43995-025-00135-y

Brunauer, S., Emmett, P. H., & Teller, E. (1938). Adsorption of gases in multimolecular layers. *Journal of the American Chemical Society*, 60(2), 309–319. https://doi.org/10.1021/ja01269a023

Lowell, S., Shields, J. E., Thomas, M. A., & Thommes, M. (2004). *Characterization of Porous Solids and Powders: Surface Area, Pore Size and Density.* Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-2303-3

Gregg, S. J., & Sing, K. S. W. (1982). *Adsorption, Surface Area and Porosity* (2nd ed.). Academic Press. https://doi.org/10.1016/C2009-0-22119-7

Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(9–10), 1051–1069. https://doi.org/10.1515/pac-2014-1117

Musa, M., Idris, S. S., Ahmad, M. M., & Yaakob, Z. (2019). Characterization of hydrochar produced from hydrothermal carbonization of oil palm shells. *Biomass Conversion and Biorefinery*, 9(4), 753–762. https://doi.org/10.1007/s13399-018-0360-7

Zhou, Y., Wu, Y., Wang, T., Zhang, J., Li, Y., & Zhao, Y. (2021). Effect of hydrothermal carbonization temperature on hydrochar properties and heavy metal adsorption performance. *Science of the Total Environment*, 754, 142175. https://doi.org/10.1016/j.scitotenv.2020.142175

Liu, Z., Quek, A., Kent Hoekman, S., & Balasubramanian, R. (2019). Production of solid biochar fuel from waste biomass by hydrothermal carbonization. *Fuel*, 103, 943–949. https://doi.org/10.1016/j.fuel.2012.07.069

Zhao, P., Shen, Y., Ge, S., Chen, Z., Yoshikawa, K., & Chen, C. (2020). Effects of process parameters on hydrothermal carbonization of biomass for energy and materials: A review. *Renewable and Sustainable Energy Reviews*, 119, 109600. https://doi.org/10.1016/j.rser.2019.109600

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for Environmental Management: Science, Technology and Implementation* (2nd ed.). Routledge, London and New York. https://doi.org/10.4324/9780203762264

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2015). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, 43, 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.02

Li, X., Hayashi, J., & Li, C.-Z. (2019). FTIR study of the evolution of functional groups during the pyrolysis of biomass: Lignin. *Fuel*, 117, 1204–1212. https://doi.org/10.1016/j.fuel.2013.01.045

Wang, T., Zhai, Y., Zhu, Y., Li, C., Zeng, G., & Wang, B. (2021). Mechanism and kinetics of hydrochar formation via hydrothermal carbonization of biomass: Insight from characterization and modeling. *Fuel*, 283, 119253. https://doi.org/10.1016/j.fuel.2020.119253

Chen, W., Lu, S., Luo, J., Shao, J., & He, Y. (2018). Characterization of biochar properties affected by different pyrolysis temperatures using FTIR and XPS analyses. *Environmental Science and Pollution Research*, 25(29), 29386–29394. https://doi.org/10.1007/s11356-018-2913-1

Chen, W., Li, K., Chen, C., & Yang, H. (2021). Thermal degradation behavior and kinetics of hydrochar and its feedstock from hydrothermal carbonization of biomass. *Bioresource Technology*, 319, 124187. https://doi.org/10.1016/j.biortech.2020.124187

Wang, L., Zhang, L., Li, A., & Chen, R. (2022). Comparative study on pyrolysis characteristics and kinetics of hydrochar and raw biomass: Insight into structural evolution during hydrothermal carbonization. *Fuel*, 308, 122017. https://doi.org/10.1016/j.fuel.2021.122017

Li, M., Xu, G., Liu, Y., & Chen, Z. (2020). Effect of hydrothermal carbonization on the physicochemical properties and combustion behavior of biomass. *Bioresource Technology*, 315, 123802. https://doi.org/10.1016/j.biortech.2020.123802