

RESEARCH ARTICLE

TRANSFORMATION AND CHARACTERIZATION OF BIOCHARS INTO ACTIVATED CARBON, WOOD PYROLYSIS FOR ENERGY GENERATION AT HIGH TEMPERATURES (800–1600°C)

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ABSTRACT

High-temperature pyrolysis of wood at 800–1600°C enhances biochar properties, such as high carbon content and energy density, making it suitable for energy generation. These properties can be further improved by upgrading biochar into activated carbon, expanding its potential applications. This study aims to investigate biochars' chemical, structural, and energetic properties produced through pyrolysis and assess their potential for energy generation and environmental applications, including their transformation into activated carbon. Biochar was produced from mango tree (*Mangifera indica*) wood using incomplete combustion. Characterization was conducted using X-ray diffraction (XRD), UV-visible spectroscopy, and water absorption capacity tests. Post-activation, changes in surface area, porosity, and adsorption properties were analyzed. XRD analysis revealed that the biochar was predominantly amorphous with some crystalline structures and a nanoscale grain size of 25.42 nm. UV-visible spectroscopy showed absorption peaks between 200 and 290 nm due to the biochar's low-density characteristics. The water absorption capacity exceeded 100%, increasing the sample's weight to 50 g in water. The biochar demonstrated enhanced surface area, porosity, and adsorption capacity post-activation. The findings highlight biochar's suitability for diverse applications, including energy production, nanomaterial composites, and sensing devices. Activation expanded its potential for water purification, gas storage, and energy storage systems, positioning biochar as a versatile and sustainable material. The dual characterization of biochar underscores its potential for energy and environmental applications. The significant post-activation improvements suggest that biochar can serve as a key material in addressing energy and environmental challenges. This study uniquely demonstrates the simultaneous evaluation of biochar's intrinsic and enhanced properties post-activation, offering new insights into its multifaceted applications in energy and environmental sustainability.

KEYWORDS

Carbonization Process, Energy Storage Devices, Nanoscale Crystallite Size, Surface Area and Porosity, UV Absorption

1. INTRODUCTION

Wood fuel is widely regarded as the most significant non-fossil energy source globally. Nearly half of the wood extracted from forests is used for energy production. This usage includes heating and cooking in developing countries and electricity production in developed nations (Hillring and Trossero, 2006; Sreevani, 2018). A significant portion of the global population—up to half—relies on solid fuels such as charcoal and biomass to meet energy demands. In developing nations, this dependency rises to 95%. The increasing demand for charcoal is driven by urbanization, rising commercial consumption, and the lack of readily available alternative energy sources (Bamwesigye et al., 2020). Despite its benefits as an energy source, charcoal production, when undertaken unsustainably, has detrimental environmental effects. Unsustainable wood harvesting and charcoal production contribute significantly to deforestation, forest degradation, and greenhouse gas (GHG) emissions (Chidumayo and

Gumbo, 2012). However, adopting improved charcoal production techniques and using sustainably managed resources can result in low net GHG emissions. This, in turn, can aid in mitigating climate change while providing additional energy options and revenue opportunities (Sjøløie, 2012).

Charcoal is a lightweight, black carbon residue formed by removing water and other volatile components from plant or animal material. It is commonly produced through the slow pyrolysis of wood or organic materials in a low-oxygen environment. This process, which can take several days, involves heating the material until volatile compounds like tar, water, methane, and hydrogen are removed (Van 'T Veen et al., 2021). The resulting product, primarily composed of carbon, is highly efficient for combustion. In commercial operations, this pyrolysis process occurs at extremely high temperatures in steel or concrete silos. Wood pyrolysis for biochar production has ancient roots but has been revisited in modern

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times within the context of renewable energy and carbon management. High-temperature pyrolysis, ranging from 800–1600°C, is particularly notable for producing biochar with superior carbonization, energy density, and stability (Sørmo et al., 2020). These biochars can be upgraded into activated carbon, a material valued for its adsorption and catalysis capabilities.

A group researchers conducted an early investigation into the catalytic potential of biochars derived from different biomass sources (Gholizadeh et al., 2019). This study identified critical temperature ranges for decomposing cellulose, xylan, and lignin while highlighting the activation energies required. It revealed the catalytic role of millet biochar and oak bark in enhancing bio-oil yield. However, a decline in carbon yield was also noted when December biochar was used, underscoring the complex interplay between catalytic performance and pyrolysis conditions. In other study, researcher extended this research by examining water-extractable organic compounds in biochars and their effects on aquatic ecosystems (Liu et al., 2022). The study explored the impact of pressure and temperature on biochar yield and its broader environmental implications through thermogravimetric analysis. It underscored the importance of temperature in determining biochar's chemical composition and suitability for various applications. A group researcher analyzed charcoal's chemical composition and structural properties derived from cherry pits (Surup et al., 2018). Using advanced techniques like mercury porosimetry and scanning electron microscopy, the study highlighted how different pyrolysis atmospheres influence the yield and quality of activated carbon. It demonstrated the critical role of heat treatment in modifying biomass structures to optimize activated carbon production.

A group researcher investigated the thermal stability and physicochemical properties of biochars produced from plant biomass at varying pyrolysis temperatures (Nzediegwu et al., 2020). Findings indicated that higher temperatures increased thermal stability and altered the chemical composition of the resulting biochar. This study emphasized the connection between pyrolysis conditions and the efficiency of biochars in agricultural and environmental applications. Rashidi and Yusup explored the production and refinement of activated carbon biochars. Spectroscopic techniques were employed to assess surface characteristics, revealing that higher pyrolysis temperatures reduced biochar yield while increasing carbon content (Rashidi and Yusup, 2020). The findings underscored the trade-offs in optimizing production processes and the need to tailor activated carbon properties based on feedstock characteristics. A study focused on the structural characteristics of pyrolysis carbons derived from beech wood, emphasizing the effects of temperature and particle size (Yu et al., 2018). While higher temperatures increased tar and gas outputs, they reduced carbon recovery. This research elucidated changes in functional groups and structural order, showing how particle size significantly influences pyrolysis efficiency and carbon reactivity. A group researcher examined the activation of carbons from waste wood and straw for wastewater treatment applications (Januszewicz et al., 2020). This study highlighted the role of activation processes in enhancing biochars' surface area and adsorption capacity. The findings underscored the potential of waste biomass in sustainable energy production and waste management practices.

Charcoal production remains a vital study area, even as renewable energy sources like solar power gain prominence. While numerous studies have explored wood carbonization and charcoal production, limited research has focused on charcoal's XRD analysis or its capacity to absorb UV radiation (Selvin et al., 2017). This raises intriguing questions for material science: Can a natural material serve as a UV radiation detector or composite without chemical synthesis? To address this gap, this study emphasizes simplified methods for producing charcoal and characterizing its crystallinity, porosity, and UV absorption properties. These characteristics are essential for exploring charcoal's potential in advanced applications, such as UV radiation detection and environmental monitoring. The broader implications of this research extend to developing sustainable energy systems and carbon management strategies. Improved pyrolysis techniques and producing high-quality biochar and activated carbons can play a pivotal role in reducing GHG emissions, managing waste, and promoting energy security. Moreover, integrating waste biomass into pyrolysis processes aligns with global trends toward circular economies and sustainable resource utilization.

2. PYROLYSIS

Pyrolysis is the thermal decomposition of organic molecules without oxygen, typically occurring at temperatures between 250 and 900°C (Devi et al., 2020). This process is an efficient alternative for converting waste

biomass into value-added products such as biochar, syngas, and bio-oil. During pyrolysis, the lignocellulosic components of biomass—cellulose, hemicellulose, and lignin—undergo depolymerization, fragmentation, and cross-linking at specific temperature ranges, resulting in a variety of products in solid, liquid, and gaseous states (Rjeily et al., 2021).

The solid product, biochar, is primarily carbonaceous, while the liquid product, bio-oil, contains a mixture of organic compounds. The gaseous products include carbon dioxide, carbon monoxide, hydrogen, and syngas, which comprise short-chain hydrocarbons (C1–C2). Various reactor systems are used for biochar production, such as agitated sand rotating kilns, wagon reactors, and bubbling fluidized bed reactors (Wang et al., 2020). A critical feature of fast pyrolysis technology is maintaining the residence time of fumes in the hot zone, which is essential for producing high-quality bio-oil. This is achieved by rapidly quenching or cooling the vapours to prevent secondary reactions (Mostafazadeh et al., 2018).

Slow pyrolysis is characterized by a long residence time (greater than one hour) and a low heating rate of approximately 5–7°C/min (Maniscalco et al., 2021). Compared to other pyrolysis methods, slow pyrolysis yields more char, making it particularly advantageous for applications such as soil enhancement. Biochar produced through slow pyrolysis can act as a soil conditioner, improving soil fertility and carbon sequestration. Paddle kilns are commonly used for slow pyrolysis due to their ability to manage extended heating durations (Nan et al., 2021). The type of biomass used and the pyrolysis conditions significantly affect the yield and quality of biochar. Temperature is the most critical operational factor influencing product composition. Increasing the temperature during pyrolysis typically decreases biochar yield while increasing syngas production (Shrivastava et al., 2021).

Fast pyrolysis is a thermochemical process with high potential for energy production, as it efficiently converts solid biomass into liquid bio-oil (Ansari et al., 2019). The conditions for fast pyrolysis are distinct and include:

1. Rapid heating rates exceeding 100°C/min.
2. Short residence times of 0.5–2 seconds for biomass particles and pyrolysis vapours.
3. Moderate treatment temperatures ranging between 400 and 600°C.

These conditions ensure that biomass is converted into liquid bio-oil with minimal solid residue. However, optimising fast pyrolysis requires precise control of temperature, residence time, and particle size to maximize yield and minimize unwanted by-products (Ubiera et al., 2021).

The pyrolysis process involves complex reactions that break down the structural components of biomass. As depicted in Figure 1, the mechanism begins with the thermal degradation of hemicellulose, which occurs at relatively low temperatures (200–300°C). This is followed by the breakdown of cellulose at higher temperatures (300–400°C) and, finally, the decomposition of lignin, which occurs over a broader temperature range (250–500°C) (Akubo et al., 2018). The type of biomass, heating rate, and reactor design influence the decomposition reactions.

2.1 Key Factors Influencing Pyrolysis

1. Temperature: Higher temperatures favour the production of syngas and bio-oil but reduce biochar yield.
2. Heating Rate: Slow heating rates promote char formation, while rapid rates enhance liquid and gas yields.
3. Residence Time: Extended residence times, as in slow pyrolysis, result in more stable char, whereas shorter times, typical of fast pyrolysis, prioritize bio-oil production.
4. Pressure: Atmospheric pressure is commonly used, but variations can influence product distribution and quality.

Pyrolysis remains a pivotal technology for waste biomass utilization, offering diverse applications in energy production, soil enhancement, and environmental management. Both slow and fast pyrolysis have unique advantages depending on the desired end products and applications.

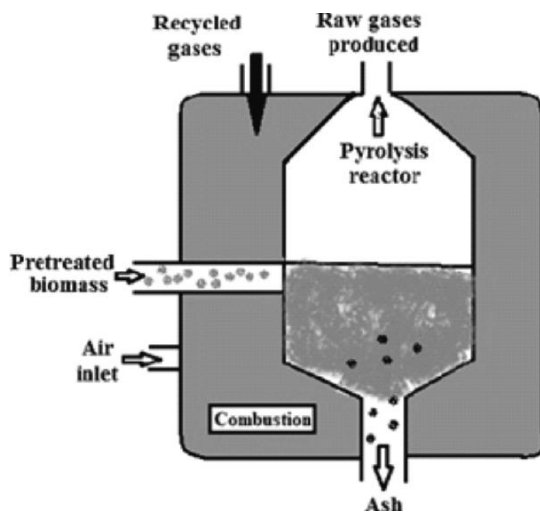


Figure 1: Pyrolysis mechanism.

The three main components of biomass are cellulose, hemicellulose, and lignin. Various reaction conditions and processes are used to transform these materials into biochar.

3. MATERIALS AND METHODS

The mango tree that was felled by an electric saw in a residential compound near Ikirun, which is located in the tropical zone with latitude 07°55'North and longitude 04°41'E of the Greenwich Meridian, is depicted in Figure 2. It is bordered by Inisha to the north, Osogbo to the south, Iragbiji to the west, and Eko-Ende to the east. The hills of Oke Afo, Oke Iba, and Oke Amola encircle the town. The tree has been around for more than 15 years. This particular food crop tree was chosen for the production of charcoal in this study because it is hardwood and can be carbonised to produce a high yield of charcoal effectively, in contrast to other types of wood that may be regarded as softwood (Sumrit and Vijitr, 2015). Without accounting for the carbonisation temperature or the kiln temperature, the entire mass of the fallen tree was burned in a locally-structured kiln, as seen in Figure 2 (with sand and fresh leaves). The characterisation of the charcoal for possible uses is the main focus.

Figure 2 shows the pieces of the fallen tree. Then, as illustrated in Figure 2, a pile of sand was placed on top of the wood pieces and covered with fresh leaves to finish the incomplete combustion process and produce the wood charcoal. After roughly 48 hours, the charcoal fragments were produced by partially burning the fresh wood, as seen in Figure 2. As the wood structure breaks down to produce charcoal, exothermic heat production takes place during carbonisation.



Figure 2: (a). Cutting down of the wood (b). Processing into smaller logs (c). Conventional Carbonization Chamber (d). Biochar Product of Carbonization

3.1 Wood Feedstock

Hardwood samples, primarily *Mangifera indica* (mango wood), were chosen due to their high lignocellulosic content, which is critical for efficient biochar production. The wood was dried to a less than 10% moisture content to ensure optimal pyrolysis performance and minimize water interference during the thermal decomposition process.

3.2 Pyrolysis Process

The dried wood samples underwent high-temperature pyrolysis in a controlled retort kiln. A continuous flow of nitrogen gas was maintained throughout the process to create an oxygen-free environment, preventing oxidation and ensuring the desired thermal decomposition. Pyrolysis was conducted at three different temperatures: 800°C, 1200°C, and 1600°C. Each temperature was held constant for 1 hour to allow for uniform carbonization and to study the temperature-dependent characteristics of the resulting biochar.

3.3 Activation Process

The biochar produced from the pyrolysis process was further enhanced through activation, employing both chemical and physical methods:

Chemical Activation: Activating agents were used to chemically treat the biochar, including phosphoric acid (H_3PO_4) and potassium hydroxide (KOH). These agents improved the pore structure, increased surface area, and enhanced adsorption capacity, making the biochar more suitable for advanced applications such as adsorption and catalysis.

Physical Activation: The biochar samples were subjected to physical activation by treating them with carbon dioxide (CO_2) gas at a high temperature of 900°C for 2 hours. This process further refined the pore network and boosted the biochar's reactivity and performance, particularly for environmental and energy applications.

This dual activation approach aimed to optimize the properties of biochar, tailoring its structure and functionality for specific applications. Combining high-temperature pyrolysis and activation processes demonstrates a systematic method for producing high-quality biochar and activated carbon from biomass feedstock.

3.4 Water Absorption

The water absorption capacity of the biochar specimens was found to vary significantly, with initial masses ranging from 50 g to 200 g and final masses increasing to 132.5 g and 468.3 g. This variation in water absorption was directly correlated with the apparent porosity of the biochar. The higher the porosity, the greater the biochar's ability to retain water. The biochar samples were immersed in water for seven days to assess this property. This extended soaking period allowed the material to achieve full saturation, accurately measuring its porosity and water retention capability. Such data are crucial for evaluating the biochar's potential applications in soil amendment and water treatment, where high porosity and absorption are desirable traits.

3.5 Characterization Techniques

The biochar was subjected to advanced characterization techniques to evaluate its optical and structural properties:

UV-Vis Spectrophotometry: The optical properties of the biochar granules were analyzed using a double-beam spectrophotometer (UV-6300PC, Model VWR). The samples were prepared at room temperature in distilled water with a neutral pH of approximately 6.9. This analysis provided insights into the biochar's light absorption and potential for applications in catalysis and filtration.

X-Ray Diffraction (XRD): Structural characteristics of powdered biochar were determined using a powder X-ray diffractometer (Model: EMPYREAN) with Cu-K radiation. The test conditions included a tube voltage of 50 kV, a tube current of 80 mA, and a 4°/min scanning speed. The XRD analysis revealed the biochar's crystalline structure and mineral composition, which is essential for understanding its thermal stability and reactivity in various applications.

4. RESULTS AND DISCUSSION

4.1 Pyrolysis and Biochar Characteristics

The biochar yield decreased as the pyrolysis temperature increased, with substantial mass loss observed at 1600°C. This reduction was primarily attributed to the volatilization of non-carbon elements, which intensified at higher temperatures. Elemental analysis revealed a marked increase in carbon content, reaching 92% at 1600°C, signifying advanced carbonization. Concurrently, the oxygen and hydrogen content diminished significantly, indicating the removal of functional groups and volatile compounds. These changes highlight the enhanced carbonization levels achieved at elevated temperatures, resulting in higher carbon purity and stability biochar suitable for applications requiring robust carbon-rich materials.

4.2 X-Ray Diffraction

Figure 3 presents the generated charcoal powder's XRD pattern. The pattern displays a narrow peak at a 2 Theta value of 29.27°, accompanied by significant noise, suggesting that the charcoal is predominantly amorphous. This is consistent with the nature of carbon, the primary component of charcoal, typically non-crystalline, except for possible traces of crystalline graphite. The XRD analysis reveals that the charcoal exhibits a mix of amorphous and somewhat crystalline characteristics. The clear diffraction peak at 29.27° indicates a small crystalline structure, likely due to graphite, while the overall pattern reflects the amorphous nature of the charcoal. The presence of noise further confirms the complexity and heterogeneity of the material, with the amorphous regions dominating the XRD profile (Nurhilal et al., 2021).

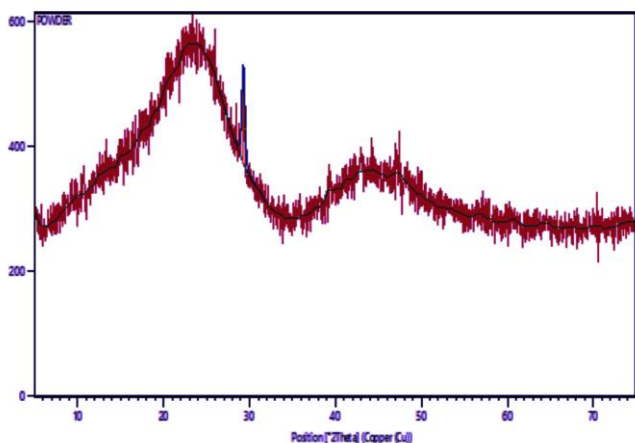


Figure 3: XRD pattern of ground charcoal sample

The crystallite size of the charcoal granules was calculated to be 25.42 nm using Debye-Scherrer's equation, $g = k\lambda/\beta$, where g represents the crystallite size, λ is the X-ray wavelength (1.54×10^{-10} nm), and β is the full width at half maximum (FWHM) of the diffraction peak. The resulting crystallite size indicates that the charcoal particles are at the nanoscale, demonstrating their potential for various applications. This nanoscale characteristic is especially useful in the development of composite nanomaterials, such as electrical sensors and photocatalytic materials. Charcoal's ability to absorb ultraviolet solar energy, as discussed further in the optical analysis section, enhances its suitability for these applications (Zhou et al., 2018). The small crystallite size enables efficient surface area utilization and interactions with other materials, making the charcoal an excellent candidate for advanced technological applications in environmental and energy sectors.

4.3 Optical Analysis

Figure 4 illustrates the absorption spectrum of the ground charcoal sample. The electromagnetic spectrum, which encompasses a wide range of wavelengths from gamma rays to radio waves, contains distinct bands associated with different types of radiation. This study focuses on the UV region of the spectrum, which spans from approximately 200 nm to 380 nm. UV radiation is divided into three categories based on wavelength: UVA (320–400 nm), UVB (280–320 nm), and UVC (200–280 nm). The charcoal sample exhibits notable absorption peaks within the 200 nm to 290 nm range, corresponding to the UVC and UVB regions. A smaller peak is also visible around 370 nm, aligning with the UVA region.

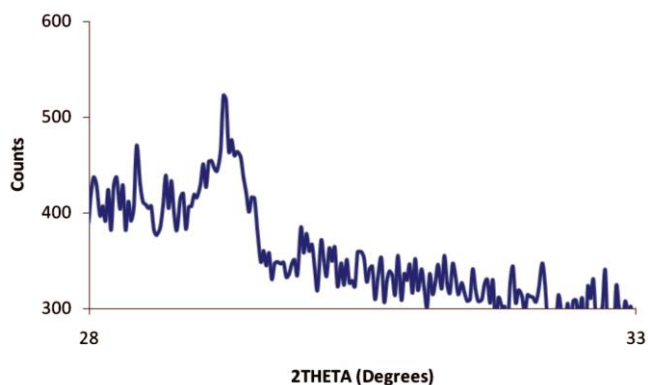


Figure 4: Absorption Spectrum of Ground Charcoal in the UV Range

The spectra indicate a steady decline in absorption as the wavelength increases into the visible spectrum, where the material shows minimal light absorption. These findings suggest that ground charcoal can absorb UV radiation, particularly in the UVC and UVB ranges. This characteristic is of great importance in environmental and health concerns, especially given the increasing depletion of the ozone layer (Chen et al., 2022). The degradation of the ozone layer allows more UV radiation to reach the Earth's surface, increasing exposure to harmful UV rays. The ability of charcoal to absorb these UV rays makes it a promising candidate for applications such as UV detectors, which can help monitor and mitigate the risks associated with elevated UV radiation levels (Durairaj et al., 2022).

4.4 Water absorption Analysis

Table 1 provides a summarized analysis of the water absorption capabilities of carbonized wood charcoal based on an experiment conducted with four samples of varying initial masses. The sample masses ranged from 50 g to 200 g, and all samples were soaked in water for a uniform period of 168 hours. The final weight of each soaked sample was recorded, and it was observed that the amount of water absorbed was directly proportional to the initial weight of the dry charcoal. Specifically, the final weight of the wet charcoal increased significantly as the sample mass grew, demonstrating that the sample's bulk or mass influences the charcoal's water absorption capacity.

As seen in Table 1, the amount of water absorbed by the charcoal increased steadily with each increase in the sample mass. The water uptake ranged from 82.5 g for the smallest sample (50 g) to 268.3 g for the most significant sample (200 g). This demonstrates that the charcoal's ability to absorb water is linked to its mass, with larger samples exhibiting higher water retention. This trend suggests that the porosity of the charcoal is directly associated with the amount of matter present in the sample. Larger quantities of particulate matter create more voids or spaces within the charcoal structure, allowing higher water absorption (Ahmed et al., 2022).

S/N	Initial Weight	Final Weight	Time
1	50g	132.5g	168 hours
2	100g	240.7g	168 hours
3	150g	352.1g	168 hours
4	200g	468.3g	168 hours

The high porosity of the charcoal can be attributed to its low density and the significant surface area of the carbonized structure. Charcoal's porous nature allows it to trap water molecules more effectively, especially when using a polar solvent like water. This high surface area enhances the material's ability to absorb and retain water. Furthermore, the low mechanical strength of charcoal contributes to its ability to expand and absorb a greater volume of water. The fact that the samples experienced a weight increase of over 100% within the 168-hour soaking period further attests to the material's high-water absorption capability (Ahmed et al., 2022).

4.5 Energy and Environmental Applications

Biochars, with their high carbon content and energy density, are highly suitable for use as industrial fuels, providing a sustainable alternative to traditional fossil fuels. When activated, biochars transform into activated carbons, which possess excellent adsorption properties, making them ideal for environmental applications such as water filtration, air purification, and gas storage. Their high surface area and porosity enhance their capacity to adsorb and store various substances (Sakhiya et al., 2020). This characteristic also makes biochar-based materials promising candidates for energy storage devices, particularly supercapacitors, where they can contribute to efficient energy storage and quick discharge, advancing clean energy technologies.

5. DISCUSSION

The pyrolysis process plays a significant role in shaping the final properties of biochar. The observed decrease in biochar yield with increasing pyrolysis temperature is consistent with the thermal degradation of volatile components. At higher temperatures, especially at 1600°C, the loss of volatile matter leads to a substantial mass reduction, primarily attributed to the volatilization of non-carbon elements (Hassan et al., 2020). This behavior is typical of biochars produced at high temperatures, where carbonization levels improve and non-carbon elements like hydrogen and oxygen are removed. As the pyrolysis

temperature increases, elemental analysis confirms a marked increase in carbon content, reaching up to 92% at 1600°C. This represents a significant enhancement in the carbonization process, indicating that elevated temperatures foster the formation of more stable, highly carbonized structures (Wang et al., 2018). The reduced oxygen and hydrogen content at higher temperatures suggests that volatile compounds and functional groups, which might interfere with biochar's stability and reactivity, are eliminated. The high carbon content achieved at 1600°C is particularly valuable for applications requiring materials with high chemical stability and low reactivity. This enhanced stability is essential for using biochar in long-term applications like soil amendment, where high levels of carbon can contribute to improved soil fertility and reduced greenhouse gas emissions (Zhang et al., 2020). Furthermore, the increased carbon purity at higher pyrolysis temperatures makes the biochar more suitable for advanced industrial and environmental applications where robust, carbon-rich materials are required.

XRD analysis provides insight into the crystallinity and structural characteristics of the biochar. The XRD pattern of the ground charcoal sample shows a narrow peak at a 2 Theta value of 29.27°, suggesting the presence of some crystalline regions. This diffraction peak indicates the presence of graphite-like structures in the charcoal, while the overall pattern, dominated by significant noise, points to the material's predominantly amorphous nature (Muigai et al., 2020). Amorphous carbon in biochar is a characteristic feature of low-temperature pyrolysis, while the small crystalline regions could represent a fraction of more stable graphite-like carbon. This mixed phase of amorphous and crystalline structures in biochar is not uncommon and depends on the specific pyrolysis conditions and the feedstock used (Muigai et al., 2020). The crystallite size of the biochar granules was determined to be 25.42 nm using the Debye-Scherrer equation. This nanoscale size indicates that the charcoal particles have a high surface-to-volume ratio, essential for various technological applications. The small crystallite size is beneficial for developing composite nanomaterials, such as electrical sensors and photocatalytic materials, as it allows for more efficient interactions with other materials (Gonçalves et al., 2020). The nanoscale dimension enhances the surface area for adsorption and catalysis, which can be exploited in energy and environmental technologies.

The optical analysis, specifically the absorption spectrum of the ground charcoal sample, reveals significant absorption in the UV range, particularly in the UVC and UVB regions (200–290 nm). This is crucial because UV radiation is known to be harmful to living organisms, and the increasing ozone layer depletion has led to elevated levels of UV exposure at the Earth's surface. The ability of charcoal to absorb UV rays, especially in the UVC and UVB regions, makes it a promising material for UV radiation protection applications (Chen et al., 2024). The UV absorption properties of charcoal can be attributed to its unique molecular structure and high surface area, which allows it to interact efficiently with UV radiation. This characteristic suggests that biochar could be used in developing UV detectors or as a component in protective coatings that mitigate the effects of UV radiation. In a broader context, charcoal's UV absorption capacity could contribute to creating materials designed to reduce the risks associated with increased UV radiation, such as skin cancer and cataracts, while protecting agricultural and industrial materials from UV degradation (Kumar et al., 2024). Furthermore, the decline in absorption as the wavelength increases into the visible spectrum indicates that charcoal does not significantly absorb light in this range, which is consistent with its use in UV protection. The high efficiency of UV absorption and the relatively low absorption in the visible spectrum make charcoal an ideal candidate for various protective and energy-harvesting applications, such as in solar energy systems or UV-blocking materials.

The water absorption analysis in Table 1 demonstrates that its mass and structural properties strongly influence biochar's water absorption capacity. The results indicate a clear correlation between the mass of the biochar samples and their water absorption capacity, with larger samples absorbing more water. The significant increase in the weight of the charcoal samples after soaking for 168 hours further emphasizes the material's high porosity. This high porosity is a key characteristic of biochar linked to its low density and the significant surface area available for water retention. The ability of biochar to absorb and retain water can be explained by its porous structure, which provides ample space for water molecules to be trapped (Edeh et al., 2020). The surface area of biochar plays a significant role in enhancing its water retention capacity, as more surface area allows for more substantial interaction with water molecules. The low mechanical strength of charcoal, typical of biochar produced at high temperatures, may also contribute to its ability to expand and absorb more water. This characteristic is especially beneficial for applications that require materials capable of retaining moisture over extended periods, such as in soil conditioning, moisture retention in

agricultural settings, or as a component in water filtration systems (Batista et al., 2018). The substantial increase in weight observed in the water absorption study further confirms the material's potential for applications requiring high water retention. The results suggest that biochar could be employed in environmental applications, such as improving soil water-holding capacity, enhancing irrigation efficiency, and supporting water retention in drought-prone areas (Fischer et al., 2018). Moreover, biochar's high porosity and water absorption properties may also make it an effective material for industrial applications, such as moisture control in storage facilities or as a moisture retention agent in building materials.

The high carbon content, porosity, and surface area of biochar make it an excellent candidate for a wide range of energy and environmental applications. As an industrial fuel, biochar can be a renewable alternative to fossil fuels, providing a more sustainable energy source. Its high energy density makes it suitable for combustion processes, where it can be used as a cleaner alternative to coal or other traditional fuels (Bhatia et al., 2021). Furthermore, biochar transforms into activated carbon, a material with excellent adsorption properties when activated. This transformation enhances its ability for environmental applications, including water filtration, air purification, and gas storage. In the realm of energy storage, biochar-based materials show great promise. Biochar's high surface area and porosity make it an ideal candidate for energy storage devices like supercapacitors. Supercapacitors require materials with high surface areas to store and release energy quickly, and biochar's properties are well-suited to meet these requirements. As a result, biochar-based supercapacitors could contribute to developing more efficient energy storage systems, advancing clean energy technologies, and supporting the transition to renewable energy sources.

6. CONCLUSION

This study underscores the substantial potential of high-temperature wood pyrolysis in energy generation and the enhancement of biochar into activated carbon. Through the carbonization process, which involves the partial combustion of fresh wood, charcoal with significant characteristics was produced. The results revealed that the charcoal produced at elevated temperatures, particularly at 1600°C, exhibited a unique blend of partially crystalline and amorphous forms. The charcoal material demonstrated nanoscale grain size with a crystallite size of 25.42 nm, contributing to its suitability for advanced applications. The ability of charcoal to absorb UV light, particularly in the UVC and UVB regions (200–290 nm), further highlights its potential in diverse environmental and energy sectors, especially in mitigating the harmful effects of increased UV radiation. The study revealed a strikingly high water absorption capacity of the charcoal, with water uptake exceeding 100% in specific samples.

This high water retention is primarily due to the charcoal's porosity, influenced by its low density and the expansive surface area created during the carbonization process. Such characteristics make charcoal an ideal candidate for high water retention applications, such as soil conditioning, moisture management, and other industrial processes requiring enhanced water absorption. The findings of this study also emphasize the superior performance of high-temperature biochar in terms of carbon content and energy density. The increased carbon content (reaching 92% at 1600°C) makes biochar an attractive candidate for energy generation, offering a sustainable alternative to traditional fossil fuels. Once activated, biochars transform into activated carbons with greatly improved surface area and adsorption capabilities. These improvements make activated carbon an invaluable material for water filtration, air purification, and gas storage applications.

Furthermore, biochar-based materials show promise in energy storage devices, including supercapacitors, where their high surface area and excellent adsorption properties contribute to efficient energy storage and rapid discharge. This study highlights the versatility of high-temperature biochar and activated carbons, which can be harnessed for various energy and environmental applications. By providing sustainable alternatives to fossil fuels and synthetic adsorbents, biochar-based materials hold the potential to drive advancements in clean energy technologies, environmental remediation, and the development of innovative nanomaterial composites for sensing devices and other specialized applications.

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