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The effects of activated carbon from palm shell for air filter

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ABSTRACT

Air pollution around the globe and the steadily deteriorating condition of indoor air quality (IAQ) are serious environmental and health issues in today's world, as people tend to spend up to 90% of their lives indoors as part of their modern living habits. There is serious health concerns associated with poor IAQ, which include respiratory and chronic ailments. The use of activated carbon as filtering material in air cleaners has been greatly encouraged because of its higher adsorption capacity, though most of today's commercial activated carbons are made from expensive sources of coal and oil. Therefore, there is a great need for affordable and sustainable materials. Palm shells, which are produced abundantly as agricultural waste in the palm oil industry in Malaysia, are promising materials for activated carbon synthesis. The focus of this research is to examine the ability of the produced activated carbon, which is derived using palm shells, based on its structural and chemical properties, in air filtration applications. Palm shells were carbonized using a pyrolysis technique with activation using Sodium Hydroxide as the chemical agent. The produced activated carbon was then characterized using the Scanning Electron Microscopy for the shape and structure, the FTIR for the functional groups, and the TGA for the thermal stability and decomposing process. The findings indicate that the carbonization temperature plays a significant role in determining the characteristics of the palm shell activated carbon. Analysis conducted using the SEM revealed that the activated carbon created from the 600°C activation procedure possessed a strong internal porous structure, while the activated carbon created from the 550°C procedure lacked pores and that from the 650°C procedure displayed enlarged pores. FTIR analysis confirmed the presence of –O–H, C=C, and C–O functional groups, with the 600°C sample showing the most favorable surface functionality for adsorption. Furthermore, the TGA analysis illustrated that the activated carbon created from the higher-temperature procedures possessed better thermal stability.

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1. Introduction

Activated carbon, more commonly known as activated charcoal, is a porous carbonaceous solid that has been used for centuries and has a long history among civilizations due to its strong adsorptive properties. Its utilization can be traced back to ancient civilizations, such as the Egyptians, who used charcoal for water purification and medicinal purposes as early as 3750 BC [1]. Similarly, early records from India and Sri Lanka demonstrate the use of sand and charcoal mixtures for water filtration and drinking water purification, indicating an early understanding of adsorption principles and concern for public health, as displayed in the Colombo National Museum [2]. Charcoal also became popular in Europe during the 18th century, not only for deodorizing purposes but also for medicinal applications, including the treatment of poisoning and stomach disorders [3]. The systematic manufacture of activated carbon only began in the 19th century, when scientific investigations started focusing on the adsorption characteristics of carbon. Researchers became aware of the potential of heat-treated carbon materials to adsorb gases and liquids due to their porous structures [4].

Activated carbon has become a global commodity with extensive applications across industries, particularly in environmental, health, and energy sectors. Its worldwide market was valued at USD 5.70 billion in 2024 and is estimated to increase from USD 5.62 billion in 2025 to USD 10.04 billion by 2032, exhibiting a compound annual growth rate (CAGR) of 8.7% during this period. The Asia-Pacific region leads the global market, with a value of USD 2.32 billion in 2024, while China, India, and Japan are among the leading producers and consumers. This growth is driven by rapid urbanization, increasing environmental awareness, and government regulations demanding cleaner air and water [5].

The global activated carbon market is moving towards emerging applications such as carbon capture and storage (CCS), hydrogen purification, and energy storage systems. Research institutions are investigating the functionality of carbon composites that could be beneficial for specific industrial applications, such as catalytic supports or battery electrode materials [6]. The activated carbon market is dynamic, driven by technological advancements and environmental sustainability. Demand for the material is increasing, and with the accelerating transition towards circular economies, activated carbon produced from renewable resources is gaining considerable attention. The rising global demand for activated carbon has prompted research into alternative low-cost materials derived from renewable precursors. This global trend encourages the use of agricultural waste materials, as tabulated in Table 1, to reduce reliance on conventional commercial activated carbon sources.

Table 1
The use of agricultural waste materials for activated carbon production

Author (year)	Title	Research method	Findings
Razzak, M. T., Ahmad, A. L., & Shafie, S. (2024) [7]	Utilization of agro-waste biomass for activated carbon production: A step towards circular economy	Experimental analysis and sustainability review	Showed fruit peels and municipal waste as viable precursors aligned with zero-waste strategies.
Pam, A. A., Abdullah, A. H., Tan, Y. P., & Zainal, Z. (2022) [8]	Physicochemical properties of porous activated carbon prepared from palm kernel	Low-cost activation protocol	Showed palm shell has excellent microporous structure ideal for adsorption applications.

shell through a low-cost activation protocol			
Gan, Y. X. (2021) [9]	Activated Carbon from Biomass Sustainable Sources	Review and comparative analysis	Highlighted the role of biomass feedstocks and emerging technologies in AC development.
Sathasivam, S., & Chun, Y. N. (2020) [10]	Production of activated carbon from palm kernel shell and its application for the removal of phenol	Experimental production and application study	Demonstrated the suitability of palm shell-based AC for water and air purification use.
Ioannidou, O., & Zabaniotou, A. (2007) [11]	Agricultural residues as precursors for activated carbon production—A review	Literature review	Identified agro-residues like coconut and palm shells as sustainable feedstocks for AC.

2. The Characteristics of Activated Carbon

2.1 Porous Structure Characteristics

Activated carbon is well known for its porous structure, which is characterized by a high internal surface area ranging from 500 m²/g to 1500 m²/g, depending on the activation method and raw material used [12]. Its extremely high surface area makes it one of the most effective adsorbents for removing a wide variety of pollutants from both gaseous and liquid phases. The internal surface comprises an extensive network of pores in which pollutants are physically and chemically trapped during the separation process. Its surface is frequently nonpolar, enabling high-affinity interactions with nonpolar impurities such as organic solvents, volatile organic compounds (VOCs), and certain pesticides.

Another important characteristic of activated carbon is its pore size distribution. The pores are generally classified as micropores (less than 2 nm), mesopores (2–50 nm), and macropores (greater than 50 nm), with micropores contributing most significantly to the surface area and adsorption capacity. The efficiency of activated carbon in adsorbing specific molecules largely depends on the compatibility between the pore size and the molecular size of the impurities [13]. Micropore-dominated adsorbents are particularly suitable for adsorbing low-molecular-weight impurities and small compounds commonly found in air and water pollutants. Besides its physical structure, the chemical composition of activated carbon is also an important factor influencing its adsorption capacity.

2.2 Surface Functional Group Characteristics

The presence of surface functional groups affects the adsorption process. Oxygen-containing groups, such as carbonyl, hydroxyl, and carboxyl groups, are typically found on activated carbon surfaces and help determine their chemical reactivity and polarity, thereby influencing their attraction towards polar molecules. These groups also enhance the ability of activated carbon to adsorb and bind polar compounds. The surface chemistry of activated carbon can be modified through oxidation or impregnation to enhance its adsorption capacity for specific adsorbates, such as chlorinated phenols and dyes [14].

Activated carbon must possess high mechanical strength and thermal stability for industrial applications, particularly on a large scale. Its strength allows it to maintain structural integrity under

high pressures and temperatures, enabling it to undergo multiple adsorption–desorption and regeneration cycles. Its long-term durability makes it cost-effective and environmentally friendly because the material can be reused numerous times without significant loss of functionality [15].

In summary, the physical structure, pore distribution, chemical activity, and thermal stability of activated carbon contribute to its usefulness. These characteristics can be controlled through raw material selection and process modifications, making activated carbon a highly versatile material. Properties such as pore structure, surface functional groups, thermal stability, and proximate composition are important factors that affect adsorption performance.

3. Fabrication Process

3.1 The Pyrolysis Process

Pyrolysis is a significant thermal decomposition process used to convert palm shell biomass into activated carbon. Pyrolysis involves exposing palm shells to elevated temperatures under oxygen-free conditions, breaking down the organic materials and converting them into carbonaceous residues known as biochar. During this process, volatile organic matter is vaporized, leaving behind a solid carbon residue.

Pyrolysis is commonly applied in the production of activated carbon from agricultural residues because of its ability to retain the porous structure essential for adsorption applications. Palm shells contain high lignin and low ash contents, making them suitable for producing high-quality activated carbon. Thermal decomposition during pyrolysis not only increases the carbon content but also enhances the structural strength of the material [16].

Temperature, treatment duration, and heating rate must be controlled during pyrolysis because they directly affect the surface area and pore formation of the final product. Pyrolysis is usually carried out at temperatures between 400 °C and 700 °C until the palm shells are converted into charcoal [17].

One of the main advantages of pyrolysis in activated carbon production is its ability to maintain the porous structure of the precursor material, which can directly contribute to surface area development and adsorption capacity. The thermal degradation process can also improve carbon yield and the rigidity of the final material, which are important for structural stability during activation and filtration applications [18].

Various studies have established the potential of palm shells to produce high-quality activated carbon under controlled pyrolysis conditions. For instance, Zaini and Syed-Hassan (2016) applied the Taguchi design to optimize the process parameters and concluded that pyrolysis temperatures between 500 °C and 600 °C provided an optimal balance between surface area and strength [19].

3.2 Carbonization Process

Carbonization is an initial stage of the overall pyrolysis process used to convert palm shells into activated carbon. The cleaned and dried palm shells were subjected to controlled heating in a furnace. The carbonization process was carried out in a furnace preset to the desired temperatures, ranging from 500 °C to 750 °C, as presented in Table 2, to examine the influence of each parameter on the yield and quality of charcoal.

This step ensures the decomposition of cellulose and hemicellulose while preserving lignin-derived carbon, which is essential for pore development and adsorption performance [20]. Different temperature settings were used, and observations were made regarding the time required for the palm shells to turn into charcoal with minimal ash formation.

Table 2

Furnace temperature (°C) and time required to convert palm shells into charcoal (minutes)

Sample	Furnace Temperature (°C)	Time taken from palm shell to charcoal (minutes)
Sample A	550	15
Sample B	600	12
Sample C	650	12
Sample D	700	10

A steady heating rate helped prevent cracking and warping of the material, which could reduce the strength of the resulting charcoal. The initial weight of the palm shells was recorded using a weighing balance. After cooling, the charcoal was weighed again to determine the weight loss during the carbonization process. Following carbonization, the charcoal was stored in an airtight container to prevent exposure to moisture and air.

3.2 Cooling Process

After carbonization, the charcoal samples were allowed to cool naturally to room temperature before being stored in airtight containers. The samples were removed from the furnace and placed in a clean laboratory environment. The natural cooling approach was applied consistently to all samples to ensure uniform treatment before further processing.

The use of an enclosed space helps preserve the inert conditions required to maintain a high carbon content. This precaution is necessary because uncontrolled cooling and excessive exposure to open conditions can lead to oxidative degradation and a reduction in fixed carbon yield [21].

3.2.1 The Crushing and Sieving Process

After cooling, the charcoal underwent crushing and sieving before the activation process, as shown in Figure 1(a). This step is important for ensuring a uniform particle size distribution, enhancing the contact surface area between the charcoal and activating agents, facilitating effective chemical impregnation, and promoting uniform pore development during activation [22].

The charcoal was crushed into smaller granules using the crushing machine shown in Figure 1(b). It was then sieved to obtain the desired particle size range suitable for chemical activation. A uniform particle size distribution allows better heat penetration and chemical diffusion during activation, resulting in a more homogeneous porous structure and enabling the activating agent to diffuse uniformly throughout the material [23].

Furthermore, smaller particles provide a greater surface-area-to-volume ratio, which is preferable for adsorption applications such as gas filtration and wastewater treatment. After crushing, the charcoal underwent sieving using a mesh size of 300 µm, as shown in Figure 1(c). This step was performed to ensure consistency in particle size for SEM, FTIR, TGA, and proximate analyses.



Fig. 1. (a) Activated carbon sample; (b) crushing machine; (c) sieve

3.3 Chemical Activation and Drying Process

Chemical activation is the process that transforms charcoal into highly porous activated carbon, as shown in Figure 2. This process develops the pore structure by treating the carbon material with chemical activating agents. Sodium hydroxide (NaOH) was selected as the activating agent because of its potential to enhance the microporosity and total surface area of activated carbon [24].

The activation process began by soaking the ground charcoal in a chemical solution prepared at a fixed mass ratio of 1:1:2 (charcoal, activating agent, and distilled water). This ratio provides sufficient chemical exposure to the carbon surface while maintaining a suitable viscosity for mixing. A total of 100 g of charcoal was mixed with 100 g of NaOH dissolved in 200 g of distilled water.

The mixture was thoroughly stirred to ensure uniform distribution of the activating agent over the carbon particles and was left to soak for one hour at room temperature to facilitate the activation process. This step is important because it promotes the breakdown of non-carbon materials within the biomass structure [25].

The activated carbon mixture was carefully dried to remove any remaining moisture, usually at 100 °C for 24 hours. This process is crucial for ensuring consistent conditions during subsequent thermal activation or characterization, thereby producing reliable test results. The drying temperature must be controlled to prevent pore collapse and structural damage, which could affect the adsorption performance of activated carbon particles.

Depending on the sample size, drying can be performed in a laboratory oven or through exposure to sunlight. Oven drying is preferred because it provides more consistent drying conditions [26].



Fig. 2. (a) Filtration; (b) rinsing; (c) oven drying; (d) cooling and storage

4. Results and Discussion

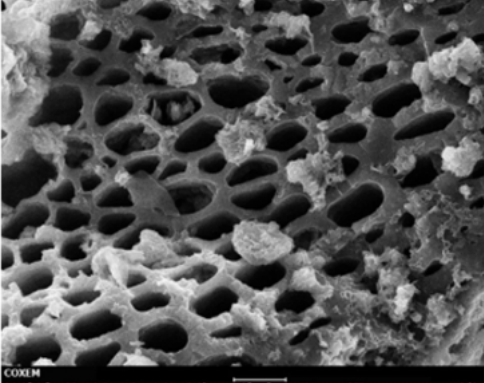
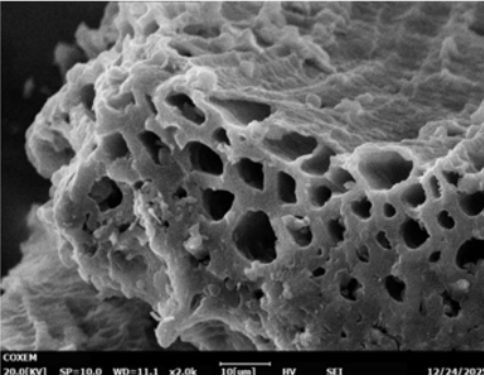
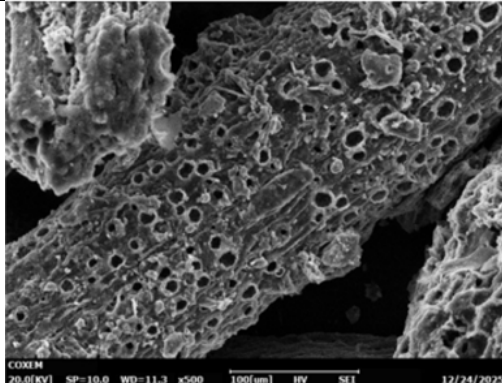
4.1 Morphological Analysis Using Scanning Electron Microscopy (SEM)

Table 3 presents the surface morphology and internal pore structure of palm shell-based activated carbon prepared at different carbonization temperatures: 550 °C (Sample A), 600 °C (Sample B), and 650 °C (Sample C). These characteristics were examined using SEM analysis. SEM images were obtained from both the surface (body) and cross-sectional views of the samples to clearly illustrate their external surface characteristics and internal pore network development.

This distinction is important because surface images reveal pore openings available for adsorption, while cross-sectional images provide information about pore depth, connectivity, and structural integrity.

Table 3

SEM micrographs of palm shell activated carbon prepared at different carbonization temperatures

Sample	Cross-sectional view	Surface (body) morphology
Sample A (550 °C)		
Sample B (600 °C)		
Sample C (650 °C)		

The SEM surface image of Sample A (550 °C) shows the initial formation of pores on the carbon surface. The surface appears relatively coarse, with visible pore openings; however, the pores have irregular shapes and an inconsistent distribution. Some regions contain partially blocked pores and residual fragments of carbonaceous material, suggesting incomplete volatilization of non-carbon components during carbonization.

This limited internal pore development is further supported by the cross-sectional SEM image. Although some internal cavities are visible, the pore channels appear shallow, with relatively thick pore walls. This suggests that, at 550 °C, the available thermal energy is sufficient to initiate pore formation but insufficient to cause significant pore expansion or interconnection. Consequently, the internal pore network remains poorly developed, which could limit the adsorption efficiency of gaseous pollutants.

The SEM surface image of Sample B (600 °C) indicates a relatively smoother and more porous surface than that of Sample A. Well-defined surface pores are evident, indicating the removal of volatile components and successful surface activation at the selected temperature. The surface also exhibits rougher and more fractured regions, which are advantageous for increasing the number of available adsorption sites.

The cross-sectional SEM image clearly shows a developed internal porous structure in Sample B, indicating successful activation at 600 °C. The porous structure appears more interconnected, with thinner pore walls and deeper pores extending into the material. The uniformly developed porous structure observed in both the surface and cross-sectional views indicates that 600 °C is a more suitable temperature for producing activated carbon with structural stability and adsorption capability.

Similar observations have been reported in previous studies of biomass-derived activated carbon carbonized at intermediate temperatures, which exhibited well-developed and interconnected pore structures due to balanced devolatilization and structural stabilization [27].

The SEM surface image of Sample C (650 °C) shows a high pore density with enlarged pore openings. The pores are noticeably larger than those in Sample B. The surface morphology indicates aggressive activation at elevated temperatures. However, the cross-sectional image of Sample C reveals signs of excessive pore enlargement and structural degradation.

Although the internal pore structure is highly developed, some regions are irregular and exhibit reduced pore wall integrity, indicating the onset of pore collapse due to over-activation. Excessive thermal treatment at higher temperatures can cause micropores to merge into larger pores, potentially influencing the adsorption selectivity and mechanical strength of the material. Excessively high carbonization temperatures can also lead to pore wall thinning and partial structural degradation in chemically activated biomass carbon.

The SEM micrographs of palm shell-based activated carbon demonstrate the development of porous structures at different carbonization temperatures. However, some samples exhibited fine, dust-like particles on their surfaces. These powdery particles may consist of residual ash or fine carbon fragments formed during crushing and sieving, or they may result from the incomplete removal of by-products following chemical activation.

Lai et al. [28] found that the presence of such surface debris in palm shell-based activated carbon is frequently caused by reactions involving mineral salts or residual chemical activating agents that were not completely removed during washing. The presence of fine surface particles is also common in biomass-derived activated carbon because of the heterogeneity of the precursor material and the breakdown of lignocellulosic structures during carbonization and activation.

Norli [29] also reported that chemically activated biomass carbon often contains surface irregularities associated with ash residues and fragmented carbon matrices. Despite the presence of

some dust-like particles, the internal pore structure remains clearly observable, particularly in the cross-sectional images. Therefore, these surface particles do not significantly affect the SEM analysis, as the primary objective is to compare morphological trends rather than to produce commercially refined activated carbon.

Overall, the SEM analysis revealed the effects of carbonization temperature on the surface morphology and internal pore structure of palm shell activated carbon. Sample A (550 °C) exhibited poor pore formation, Sample B (600 °C) demonstrated well-distributed surface pores and a highly interconnected internal pore structure, while Sample C (650 °C) showed excessive pore enlargement accompanied by structural degradation.

Based on the combined observations from the surface and cross-sectional SEM images, Sample B (600 °C) exhibited the most suitable morphology among the samples for air filtration applications. Its developed surface pores, well-connected internal pore channels, and intact structure suggest an optimal balance between pore development and structural integrity, which is essential for effective adsorption of gaseous pollutants and VOCs.

4.2 Thermal Decomposition via Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was conducted to evaluate the thermal stability and decomposition characteristics of palm shell-based activated carbon produced at carbonization temperatures of 550 °C, 600 °C, 650 °C, and 700 °C. The TGA procedure involved heating the samples at a controlled rate and measuring their weight loss at different temperatures. The TGA results presented in Figure 3 play an important role in determining the moisture content, volatile matter content, and thermal resistance of the activated carbon samples.

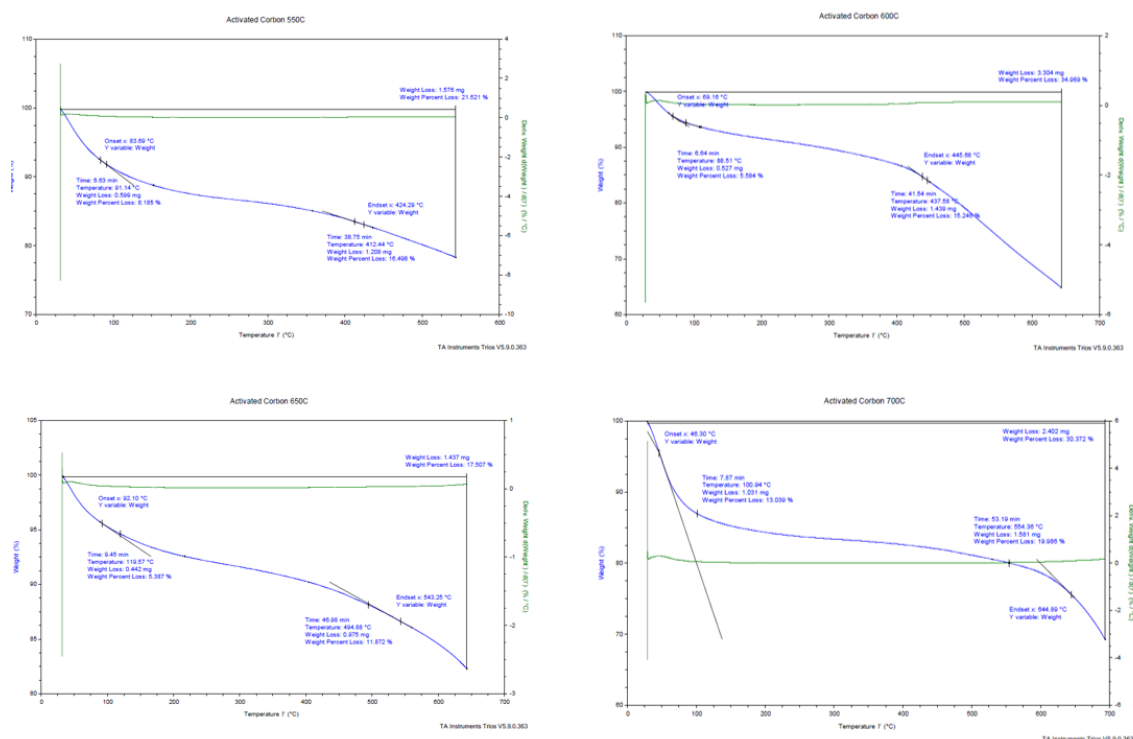


Fig. 3. TGA curves of palm shell activated carbon prepared at different carbonization temperatures

The TGA curve of the activated carbon sample produced at 550 °C shows a combined weight loss of 21.52% over a temperature range of 100 °C to 600 °C. The initial stage of weight loss below 100 °C can be attributed to the desorption of physically adsorbed moisture and low-boiling-point volatile compounds.

The subsequent gradual weight loss between approximately 100 °C and 424 °C can be attributed to the decomposition of unburned organic materials and unstable functional groups. The substantial combined weight loss indicates that the sample produced at 550 °C still contains a considerable amount of thermally unstable components, suggesting incomplete carbonization and activation.

For the activated carbon produced at 600 °C, the TGA curve indicates a considerable total weight loss of 34.99%. The initial weight loss below 100 °C is lower than that of the 550 °C sample, implying a lower moisture content. A more pronounced weight loss is observed at higher temperatures, which may be attributed to the decomposition of oxygen-containing functional groups formed during chemical activation.

Despite the higher overall weight loss, the gradual nature of the decomposition curve suggests better thermal resistance than that of the lower-temperature sample. This behavior indicates that the activated carbon produced at 600 °C underwent more extensive activation, resulting in a more developed pore structure while maintaining acceptable thermal stability.

The activated carbon produced at 650 °C exhibited a total weight loss of approximately 17.51%, which is lower than the weight losses recorded for the samples produced at 550 °C and 600 °C. The weight loss below 120 °C is minimal, indicating a lower moisture content and smaller amounts of physically adsorbed volatile compounds.

The largest weight loss occurs gradually up to approximately 543 °C, suggesting greater thermal stability. The lower weight loss and higher decomposition temperature indicate that increasing the carbonization temperature enhances thermal stability through the formation of more ordered and stable carbon structures.

The total weight loss of the activated carbon prepared at 700 °C was approximately 30.37%. Although the initial moisture-related weight loss was moderate, substantial weight loss occurred at higher temperatures, indicating the decomposition of volatile substances. The increased weight loss at elevated temperatures may be associated with over-activation, which can reduce thermal stability and weaken the carbon structure. These results suggest that excessively high activation temperatures can reduce the stability of activated carbon despite improvements in pore formation.

In general, the TGA results indicate that carbonization temperature is a key parameter influencing the thermal stability of palm shell-based activated carbon, as reported in previous studies on thermally treated biomass materials. The multistage weight loss observed in the TGA analysis is typical of biomass-based activated carbon and is consistent with previous findings. This thermal behavior is often associated with moisture evaporation, degradation of surface functional groups, and the subsequent stability of the carbon matrix [30].

Based on the results, the sample activated at 650 °C exhibited the highest decomposition temperature and the lowest total weight loss, indicating the highest thermal stability among the samples. Samples activated at lower and excessively high temperatures exhibited relatively greater weight losses due to residual volatile components or over-activation effects [31].

For practical air filtration applications, activated carbon synthesized at 650 °C is considered suitable because of its combination of thermal stability and strength, particularly where resistance to thermal degradation and long-term durability are essential.

4.3 Surface Functional Group Analysis via Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared (FTIR) spectroscopy was conducted to identify the functional groups present on the surfaces of palm shell charcoal and activated carbon. FTIR characterization was performed on palm shell-based activated carbon samples prepared at carbonization temperatures of 550 °C, 600 °C, and 650 °C, as shown in Figure 4.



Fig. 4. FTIR spectra of palm shell-based activated carbon prepared at different carbonization temperatures

The analysis was conducted on samples before activation (charcoal) and after chemical activation to evaluate the effects of activation on their surface chemical properties. The significance of these functional groups lies in their influence on adsorption properties.

The FTIR spectrum of the charcoal produced at 550 °C before activation displayed a broad absorption band in the range of 3800–3400 cm^{-1} , which is attributed to O–H stretching vibrations associated with hydroxyl groups from moisture, alcohols, or phenolic compounds present in the raw biomass material.

The peak at 1560 cm^{-1} indicates the presence of C=C bonds in aromatic rings derived from carbonaceous structures formed during carbonization. Peaks identified in the region of 1030–875 cm^{-1} are associated with C–O bonds originating from residual cellulose and hemicellulose.

After activation, the FTIR spectrum of the activated carbon produced at 550 °C exhibited distinct variations in the intensity and positions of the functional group absorption bands. The broad band at 3420–3380 cm^{-1} , corresponding to O–H stretching vibrations, became more pronounced. This indicates the formation of hydroxyl groups on the material surface due to chemical activation.

The peak at 2877 cm^{-1} represents C–H stretching vibrations, while the peak at 1508 cm^{-1} corresponds to C=C bonds in aromatic compounds. These changes indicate that chemical activation enhances surface functionality, which is beneficial for adsorption processes.

The FTIR spectrum of charcoal produced at 600 °C displayed several peaks between 3600 and 3400 cm^{-1} , which can be attributed to O–H stretching vibrations. Peaks at 3139–3109 cm^{-1} may be associated with C–H stretching vibrations in aromatic compounds.

The sharp peak at approximately 1561 cm^{-1} is associated with aromatic C=C bonds, further indicating the development of aromatic structures at higher carbonization temperatures. Peaks at 1004 cm^{-1} and 873 cm^{-1} are associated with C–O stretching vibrations.

The FTIR spectrum of activated carbon produced at 600 °C revealed a reduction in the intensity of several oxygen-containing functional groups compared with the corresponding charcoal sample. Only very weak peaks were observed at 2281 cm^{-1} and 1989 cm^{-1} , which may be assigned to C $\equiv$ C- or C=O-related vibrations.

The decrease in peak intensity suggests the effective removal of volatile components and non-carbon elements during activation, resulting in a more carbon-rich structure. This behavior is often associated with improved adsorption performance due to increased surface purity and pore accessibility.

The broad O–H stretching band in the 3800–3500 cm^{-1} region observed in the FTIR spectrum of charcoal produced at 650 °C before activation is attributed to hydroxyl groups and adsorbed moisture.

Peaks at 1543 cm^{-1} and 1509 cm^{-1} correspond to aromatic C=C stretching vibrations, reflecting the formation of stable aromatic carbon structures at higher carbonization temperatures. Additional absorption bands between 1030 and 773 cm^{-1} can be attributed to C–O stretching vibrations.

The FTIR spectrum of activated carbon produced at 650 °C also exhibited changes in functional group composition following activation. The O–H stretching band at 3556–3366 cm^{-1} remained present but showed lower intensity, indicating the partial removal of oxygen-containing groups during high-temperature activation.

Peaks at approximately 2316 cm^{-1} and 2192–2099 cm^{-1} may be attributed to C $\equiv$ C- or C=O-related vibrations. In general, the reduction in the intensity of these functional groups indicates a more graphitized carbon structure, which reduces surface polarity while providing greater thermal stability.

The FTIR analysis revealed that carbonization temperature and chemical activation play important roles in influencing the surface functional groups of palm shell-based activated carbon. Generally, the charcoal samples exhibited a wider range of oxygen-containing functional groups due to the incomplete decomposition of biomass components.

In contrast, the activated carbon samples exhibited reduced peak intensities, indicating the removal of volatile substances and the development of a more carbon-rich structure. The FTIR spectra of palm shell-based activated carbon revealed several functional groups commonly associated with biomass-derived carbon materials [32].

Broad absorption bands in the wavenumber range of 3200–3600 cm^{-1} were attributed to O–H stretching vibrations associated with hydroxyl groups and adsorbed moisture. Peaks at approximately 1600 cm^{-1} correspond to C=C stretching vibrations in aromatic carbon structures, while bands in the range of 1000–1300 cm^{-1} are associated with C–O functional groups [33].

Although the FTIR spectra exhibited overlapping and broad peaks, this behavior is common in chemically activated biomass-based carbon because of the complex and heterogeneous nature of the precursor material. Previous studies on palm shell and agricultural biomass-derived activated carbon have also reported similar trends in their FTIR characteristics [34].

The presence of oxygen-containing functional groups supports surface chemistry favorable for adsorption processes, indicating the potential suitability of the produced activated carbon for air filtration applications.

Among all the samples, activated carbon prepared at 600 °C exhibited balanced surface chemistry, with sufficient functional groups for adsorption while maintaining structural stability. Such a balance is advantageous for air filtration applications because both surface functionality and pore accessibility contribute to effective pollutant removal.

5. Conclusions

This study successfully established the potential of palm shell waste from the palm oil industry as a sustainable and renewable raw material for producing activated carbon suitable for air filtration systems. The study investigated the influence of carbonization temperature and chemical activation processes on the morphological, chemical, and thermal properties of palm shell-based activated carbon.

SEM analysis demonstrated that carbonization temperature plays a crucial role in pore formation and structural development. At a carbonization temperature of 550 °C, minimal pore development and partially blocked structures were observed, indicating incomplete carbonization. In contrast, activated carbon produced at 600 °C exhibited a well-developed porous structure, which is essential for adsorption applications. At 650 °C, excessive pore development and partial structural damage were observed due to over-activation.

The FTIR analysis revealed the presence of functional groups such as hydroxyl (O–H), aromatic carbon (C=C), and carbon–oxygen (C–O) on the surfaces of the activated carbon samples. Chemical activation using NaOH helped enhance surface functionality and remove volatile components, resulting in a higher carbon content.

Among the samples analyzed, activated carbon produced at 600 °C exhibited suitable surface functionality for the adsorption of harmful indoor gases and VOCs. Thermogravimetric analysis also demonstrated that increasing the carbonization temperature generally improved thermal stability. Although the sample produced at 650 °C exhibited the highest thermal stability, the sample produced at 600 °C demonstrated the best overall characteristics.

Although direct testing of the air filtration performance of palm shell-based activated carbon was not conducted, its potential performance was evaluated through morphological, chemical, and thermal characterization. The well-developed pore structures observed through SEM, surface functional groups identified through FTIR, and thermal stability demonstrated by TGA indicate that activated carbon prepared at 600 °C is potentially suitable for air filtration applications.

Overall, the objective of evaluating the material's potential performance was achieved based on established material characterization indicators.

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