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Development of Air-Conditioning Filter using Palm Shell Activated Carbon

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ABSTRACT

Indoor air pollution remains a significant concern for human health, particularly due to the presence of airborne particulate matter and gaseous pollutants that are not effectively removed by conventional air-conditioning filters. The utilization of agricultural biomass waste as a precursor for activated carbon offers a sustainable approach to developing alternative air filtration materials. This study aims to develop an air-conditioning filter incorporating palm shell activated carbon (PSAC) and investigate its morphological and elemental characteristics in comparison with an untreated filter and a commercial activated carbon filter. Palm shell biomass was subjected to carbonization and chemical activation processes to produce activated carbon, which was subsequently incorporated into the filter medium. The surface morphology and pore structure of the developed filter were examined using Scanning Electron Microscopy (SEM), while its elemental composition was determined through Energy Dispersive X-ray Spectroscopy (EDS). SEM observations revealed that the PSAC filter exhibited a rough, highly porous, and interconnected surface morphology, with more pronounced pore development than the untreated and commercial filters. Furthermore, EDS analysis indicated a high carbon content in the PSAC filter, confirming the successful conversion of palm shell biomass into carbon-rich material. Minor mineral elements were also detected, potentially originating from the inherent ash constituents of the biomass and residual chemicals used during activation. Overall, the findings demonstrate the feasibility of incorporating palm shell-derived activated carbon into air-conditioning filter media, highlighting its potential as a sustainable and value-added alternative to conventional filtration materials. Further investigations into particulate filtration efficiency, gaseous pollutant adsorption capacity, and airflow resistance are recommended to establish its practical filtration performance.

1. Introduction

Air pollution remains a significant environmental and public health concern, particularly in indoor environments where prolonged exposure to airborne contaminants can adversely affect human

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health. Poor indoor air quality (IAQ) has been associated with various health complications, including respiratory diseases, allergic reactions, and chronic health conditions. Although conventional air-conditioning systems are widely employed to maintain thermal comfort, their filtration components may be insufficient for effectively removing gaseous pollutants, such as volatile organic compounds (VOCs), fine particulate matter (PM), and odorous compounds. Because people spend a substantial proportion of their time indoors, the development of efficient, sustainable, and cost-effective air filtration materials has become increasingly important for improving IAQ and minimizing exposure to harmful airborne contaminants [1].

In recent years, biomass-derived activated carbon has attracted considerable research interest as a sustainable adsorbent for air purification applications. Among the available biomass resources, palm kernel shell (PKS), an abundant agricultural by-product generated by the palm oil industry, has demonstrated considerable potential as a precursor for activated carbon production. The lignocellulosic composition of PKS, consisting primarily of cellulose, hemicellulose, and lignin, contributes to its relatively high carbon content and facilitates the development of porous carbon structures during carbonization and activation. Furthermore, converting PKS into palm shell activated carbon (PSAC) provides an environmentally sustainable approach to agricultural waste valorization while reducing dependence on conventional fossil-based carbon precursors. Previous studies by Zaini et al. [2] and Rashidi and Yusup [3] have demonstrated the potential of PKS-derived activated carbon for carbon dioxide (CO₂) and methane (CH₄) adsorption. Additionally, Gopalan et al. [4] highlighted the environmental benefits of biomass-derived carbon materials, emphasizing their potential contribution to carbon emission reduction and circular economy practices.

2. Literature Review

Activated carbon is a highly porous carbonaceous material characterized by its extensive specific surface area, typically ranging from 500 to 1,500 m²/g, and well-developed pore structure, which collectively contribute to its adsorption performance [6]. Activated carbon is commonly produced from carbon-rich precursors, including coal, coconut shells, agricultural residues, and synthetic polymers, through carbonization followed by physical or chemical activation [7]. Carbonization involves the thermal decomposition of organic constituents under oxygen-limited conditions, whereas activation promotes pore development and increases the accessible surface area of the carbon material. Physical activation generally involves oxidizing agents such as steam or carbon dioxide, while chemical activation employs activating agents such as potassium hydroxide (KOH) to modify the carbon structure and enhance pore formation. The selection of activation techniques and processing conditions significantly influences pore size distribution, surface chemistry, and adsorption characteristics, thereby determining the suitability of activated carbon for gas-phase adsorption and liquid-phase purification applications [8].

The adsorption performance of activated carbon is strongly influenced by its pore architecture, particularly the presence of micropores with pore widths below 2 nm. Microporous activated carbon commonly exhibits Type I adsorption isotherms, indicating substantial adsorption capacity at relatively low pressures due to micropore filling. Such characteristics are particularly advantageous for the adsorption of gaseous molecules, including CO₂ and CH₄. Zaini et al. [9] reported a CH₄ adsorption capacity of approximately 3.2 mmol/g at 25 °C for PKS-derived activated carbon, which was attributed to its developed microporous structure, micropore volume exceeding 0.6 cm³/g, and favorable surface characteristics. Gas adsorption on activated carbon is predominantly governed by physisorption, involving van der Waals interactions and pore-filling mechanisms, although surface functional groups may enhance specific interactions with polar or quadrupolar molecules such as

CO₂. Furthermore, adsorption kinetics may be described using pseudo-first-order or pseudo-second-order models, depending on the adsorbate–adsorbent system and experimental conditions. However, fitting a pseudo-second-order kinetic model does not necessarily indicate that chemisorption is the dominant adsorption mechanism. The development of an effective pore network is closely associated with activation parameters, including activation temperature, treatment duration, activating agent concentration, and impregnation ratio. These parameters influence carbon gasification, pore widening, and the formation of interconnected microporous and mesoporous structures.

Optimized activation conditions can promote the formation of narrow micropores and slit-shaped pore structures, which are particularly beneficial for gas adsorption through enhanced adsorbate–surface interactions. Conversely, excessive activation may result in pore widening, structural deterioration, and reduced carbon yield. Therefore, systematic optimization of the activation process is essential to achieve a balance between specific surface area, pore size distribution, carbon yield, and adsorption efficiency. Understanding these relationships is particularly important for developing PKS-derived activated carbon as a sustainable adsorbent for indoor air purification applications. PSAC outperforms many biomass-derived carbons in gas adsorption due to its unique physicochemical properties, particularly its narrow micropore distribution centered at 0.7 nm. Prasetyo et al. [10] revealed that nanoporous PSAC achieves CO₂/CH₄ selectivity ratios of 12:1 at 30 °C, surpassing coconut shell carbons (8:1) owing to optimal molecular sieving of CO₂ with a kinetic diameter of 0.33 nm. This selectivity is crucial for biogas upgrading and landfill gas purification. Life-cycle analyses [11] show that PSAC production reduces greenhouse gas emissions by 65% compared to conventional methods, primarily by avoiding fossil precursors and utilizing agricultural waste. The mechanical strength of PSAC (>50 N crush resistance) also ensures longevity in fixed-bed reactors, minimizing attrition losses during cyclic adsorption-desorption operations.

However, feedstock variability remains a challenge, with shells from different palm species exhibiting divergent ash content (2–10%) and fixed carbon (70–85%). Rashidi and Nor Adilla [16] addressed this via steam activation standardization at 800 °C, achieving consistent surface areas (±5% deviation). Emerging strategies include hybrid activation with CO₂ followed by KOH to develop hierarchical pore structures, enhancing diffusion kinetics for high-flow applications like automotive cabin filtration. Córdoba-Ramírez et al. [17] demonstrated that torrefied PKS activated with H₃PO₄ achieves 25% greater CO₂ uptake than untreated shells by removing hemicellulose-derived volatiles that impede pore development. These advances solidify PSAC's role in meeting global carbon capture demands while adhering to circular economy principles. Table 1 summarizes the adsorption performance of various biomass-derived and carbon-based materials. Studies demonstrate that carbon nanotubes, activated carbon fibers, and carbon composites exhibit excellent filtration and adsorption capabilities. Advanced fabrication techniques, particularly two-step activation, enhance surface area, porosity, and adsorption efficiency. These findings highlight the potential of carbon-based materials for effective pollutant removal and environmental applications.

Table 1

Comparison of different biomass-derived carbons for gas adsorption

Author (year)	Topic	Research method	Findings
Norli et al. (2024) [12]	Carbon nanotubes or activated carbon fiber-based air filter media for simultaneous removal of particulate matter and ozone	- Fabricated CNT/ACF filter media via chemical vapor deposition.	- PM Filtration: CNT/ACF achieved >95% removal efficiency for mid-range particle size (~145.9 nm), classifying it as HEPA H11-level. - Efficiency Enhancement: The CNT growth increased the quality factor by 48%, with only a 36% rise in pressure resistance.
Tsuyoshi Yoda et al. (2019) [13]	ACF preparation from rayon via thermal treatment for enhanced adsorption performance	- Employed single- and two-step thermal treatments for fabricating rayon-derived ACF.	- MB Removal: Two-step processing yielded higher capacity filters, demonstrating superior adsorption performance vs. single-step approaches. - Surface Area: Achieved 500 m ² /g BET specific area
H. Alhussain, et al. (2024) [14]	Developing Lignosulfonate-Based Activated Carbon Fibers (LACFs)	- LACFs produced via electrospinning, carbonization, and two-step activation.	- Mesoporosity: Developed ACF with a high specific surface area (643.89 m ² /g) and enhanced mesoporosity (~65%). - Optimization: Two-step activation resulted in lower weight loss while improving porosity and surface area compared to one-step methods. - Adsorption Efficiency: Excellent methylene blue adsorption capacity of 1142 mg/g.
N. Kumar (2026) [15]	Activated Carbon–Carbon Composites for Adsorption Applications	- Developed AC–carbon composites (ACCC) using mesophase pitch-based carbon fibers and phenolic resin. - Characterized porosity, adsorption efficiency, and resistivity. - Used methylene blue and VOC adsorption tests.	- Adsorption Performance: ACCC exhibited excellent removal of volatile organic compounds (VOCs), with a BET surface area of 800 m ² /g. - Conductivity: High electrical conductivity (~470 μΩ·m) due to mesophase pitch-based fibers. - Microporosity & Stability: Micropores (0.34 mL/g) offered high adsorption capacity.

3. Methodology

The preparation of palm shell charcoal was carried out through a series of sequential processes, including carbonization, grinding, sieving, chemical activation, and drying. Figures 1(a) and (b) illustrate the physical appearance of palm shells before and after carbonization, respectively. Initially, the palm shells were carbonized at temperatures ranging from 500 to 750 °C under a controlled heating rate of 10 °C/min. The samples were maintained at the respective carbonization temperatures until visible smoke emission ceased, which was used as an operational indicator of carbonization completion. Subsequently, the carbonized samples were collected and stored in airtight containers to minimize exposure to atmospheric moisture and prevent potential

contamination prior to further processing. Following carbonization, the resulting charcoal was mechanically ground to reduce particle size and facilitate subsequent chemical activation, as shown in Figure 1(c). The ground charcoal was visually inspected to remove incompletely carbonized particles and residual impurities before being subjected to sieving using a series of sieves with aperture sizes of 0.300, 0.150, and 0.075 mm. This process was performed to obtain the desired particle size fractions and promote a more uniform particle size distribution. Controlling particle size is important for facilitating consistent heat transfer and improving the diffusion of chemical activating agents throughout the carbon matrix during activation [18]. Furthermore, particle size reduction increases the external surface area available for contact with activating agents, potentially promoting more homogeneous pore development and improving the accessibility of adsorption sites. These structural characteristics may subsequently enhance the adsorption performance of the activated carbon by facilitating the diffusion and retention of gaseous contaminants, including volatile organic compounds (VOCs) and odorous substances, within its porous structure [19].



Fig. 1. Palm shells: (a) before carbonization; (b) after carbonization; (c) grinding machine

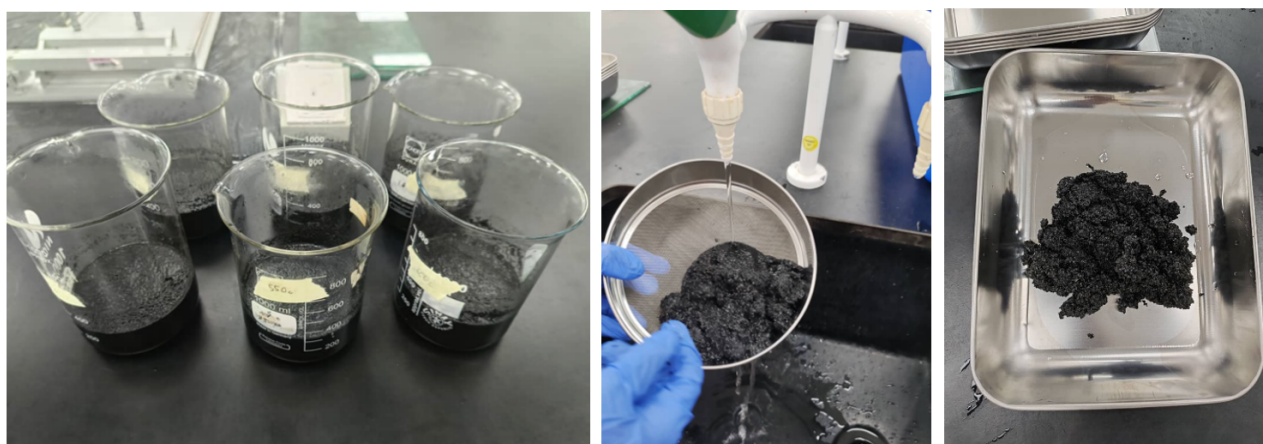


Fig. 2. Palm shells: (a) soaked in sodium hydroxide (NaOH); (b) rinsing of the palm shells; (c) rinsed palm shells on a metal tray

Following grinding and sieving, 100 g of palm kernel shell (PKS) charcoal was immersed in an alkaline solution prepared by dissolving 100 g of sodium hydroxide (NaOH) in 200 g of distilled water, corresponding to a charcoal-to-NaOH-to-water mass ratio of 1:1:2. The charcoal was soaked in the prepared solution for 1 h to facilitate chemical impregnation, as illustrated in Figure 2(a). Subsequently, the treated charcoal was thoroughly rinsed with distilled water and filtered to remove residual NaOH and soluble impurities. The resulting alkaline wastewater was collected in a designated laboratory waste container to ensure safe handling and disposal. Following rinsing, the charcoal samples were transferred onto a metal sample tray, as shown in Figure 2(b), and dried in a laboratory oven at 100 °C for 24 h to eliminate residual moisture prior to further processing.



Fig. 3. (a) Palm shells being dried in an oven; (b) non-woven fabric material; (c) synthetic fibre fabric material

Figure 3(a) illustrates the oven-drying process of palm shells, which was conducted to reduce their moisture content prior to subsequent processing. Following drying, the palm shells were allowed to cool naturally to room temperature to minimize moisture condensation and thermal shock during handling. The dried palm shells were subsequently stored in airtight containers to prevent moisture absorption and maintain their condition before filter fabrication [20]. Two types of filter media were employed in this study, namely non-woven fabric and synthetic fibre fabric, as illustrated in Figures 3(b) and 3(c), respectively. The fabrication of PSAC-based filters was initiated by applying a uniform layer of water-based acrylic adhesive onto the surface of the filter media using a roller. The adhesive was selected based on its compatibility with PSAC and its ability to facilitate particle attachment without significantly affecting the carbon material. Subsequently, PSAC granules were uniformly distributed over the adhesive-coated fabric using a sieving technique to achieve consistent particle coverage. The coated fabric was then subjected to compression using a hydraulic press to enhance adhesion between the PSAC granules and the filter substrate. Following compression, the fabricated filters were oven-cured at 80 °C for 1 h to promote adhesive curing and improve particle bonding [21]. The filters were subsequently inspected for weight consistency, uniformity of PSAC distribution, and visible surface defects. The same fabrication procedure was applied to both non-woven and synthetic fibre fabrics to ensure consistency in the preparation process.



Fig. 4. (a) Non-woven PSAC filter before (left) and after (right) fabrication; (b) synthetic fibre PSAC filter before (left) and after (right) fabrication

Figures 4(a) and 4(b) illustrate the PSAC-based filter before and after the fabrication process, respectively. Visual examination of the fabricated filters revealed that the PSAC particles were uniformly distributed and adequately bonded to the fabric surfaces using the selected water-based acrylic adhesive. No significant particle detachment, peeling, or irregular distribution was observed, suggesting satisfactory adhesion between the PSAC granules and the filter media. Effective particle bonding is essential for maintaining the structural integrity of the fabricated filters, as insufficient adhesion may result in carbon particle loss during operation, potentially reducing filtration efficiency and long-term performance [22]. These observations demonstrate the feasibility of incorporating PSAC granules into non-woven and synthetic fibre filter media through a relatively simple fabrication process. The resulting PSAC-based filters exhibit promising characteristics for potential application in air-conditioning filtration systems, although further evaluation of their adsorption efficiency, airflow resistance, and mechanical durability is necessary to establish their operational performance.

4. Results and Discussion

4.1 Scanning Electron Microscopy (SEM)

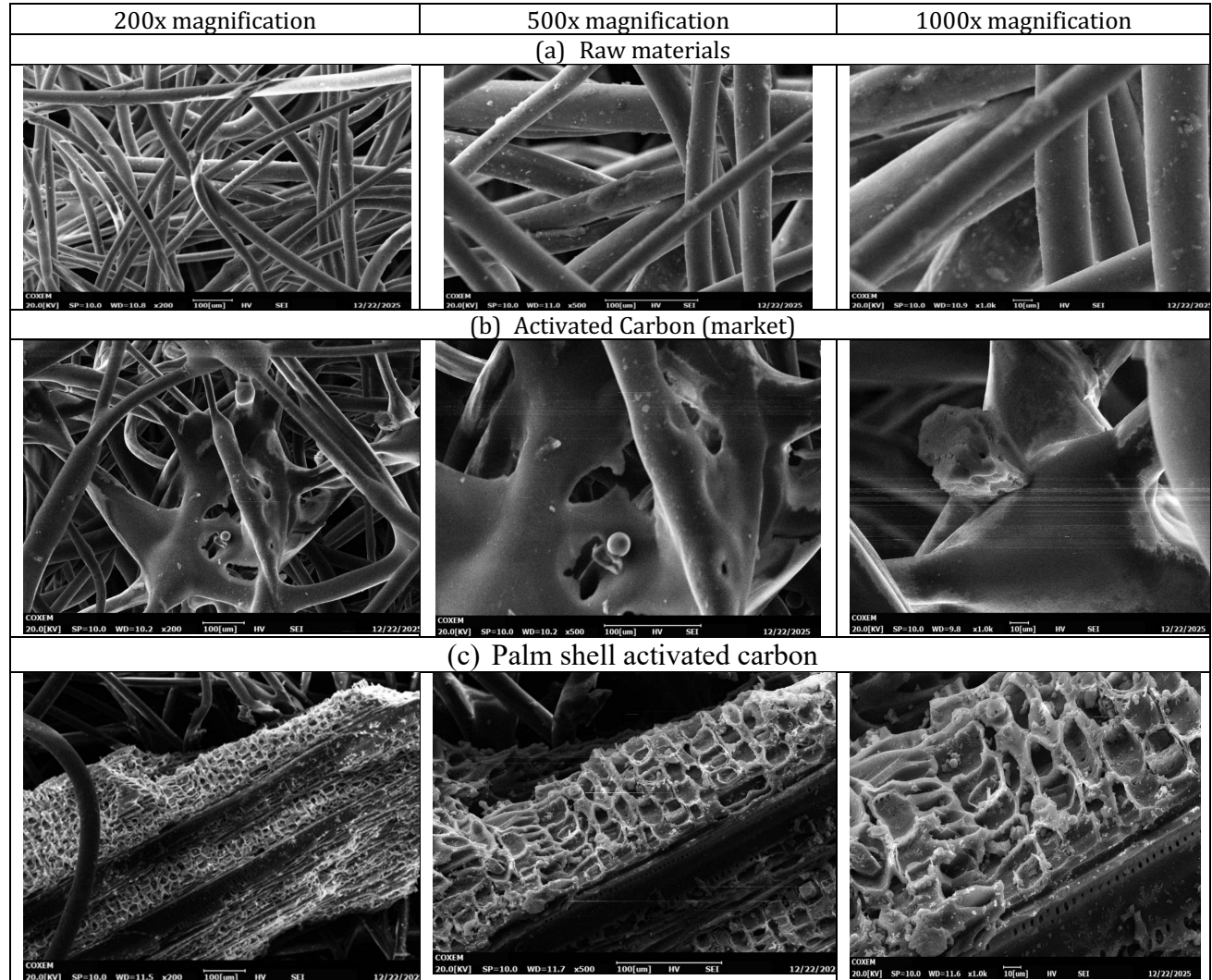
Scanning electron microscopy (SEM) was employed to investigate the surface morphology and microstructural characteristics of three filter materials: the raw filter, a commercially available activated carbon filter, and the developed palm shell activated carbon (PSAC) filter. SEM micrographs were obtained at magnifications of 200 $\times$, 500 $\times$, and 1,000 $\times$ to evaluate differences in fibre arrangement, surface texture, carbon distribution, and visible pore structures. Energy-dispersive X-ray spectroscopy (EDS) analysis was additionally conducted to determine the elemental composition of the filter materials and complement the morphological observations. The corresponding SEM micrographs and EDS results are presented in Table 2.

The SEM micrographs of the raw filter revealed a randomly oriented, non-woven fibrous structure characterized by relatively large inter-fibre spaces. At 200 $\times$ magnification, the loosely arranged fibres exhibited substantial void regions, which may facilitate airflow through the filter medium while enabling the physical interception of airborne particles. At higher magnifications of 500 $\times$ and 1,000 $\times$, the fibre surfaces appeared relatively smooth and uniform, with minimal surface irregularities and no clearly distinguishable porous features. These morphological characteristics suggest that the raw filter primarily functions through mechanical filtration mechanisms rather than adsorption. Nevertheless, the absence of visible pores in the SEM micrographs does not necessarily indicate a

complete absence of adsorption sites, as nanoscale porosity cannot be adequately resolved at the investigated magnifications.

Table 2

SEM images at different magnifications of (a) raw material; (b) activated carbon; (c) palm shell activated carbon



In contrast, the commercially available activated carbon filter exhibited noticeable morphological differences compared with those of the raw filter, particularly in terms of surface roughness and carbon deposition. At 200× magnification, the fibrous network appeared partially coated with activated carbon particles, resulting in reduced inter-fibre spacing and a more compact surface structure. At 500× magnification, the carbon-coated regions displayed increased surface irregularities, heterogeneous textures, and visible openings within the deposited carbon layer. Further examination at 1,000× magnification revealed a relatively porous surface morphology with irregular voids and cavities, suggesting the development of accessible pathways that may facilitate gas diffusion towards adsorption sites. The presence of these structural features potentially contributes to improved adsorption performance by increasing the accessibility of gaseous contaminants to the activated carbon surface. However, the identification and quantification of micropores and mesopores require complementary pore characterization techniques, such as nitrogen adsorption–desorption analysis [23]. Among the investigated filter materials, the developed

PSAC filter exhibited the most pronounced morphological modifications, characterized by extensive carbon coverage, increased surface heterogeneity, and numerous visible void structures [24].

At 200× magnification, a relatively thick and continuous carbonaceous layer was observed, accompanied by irregularly distributed cavities across the filter surface. These features indicate substantial deposition of the palm shell-derived activated carbon onto the filter substrate. At 500× magnification, the carbon surface exhibited a heterogeneous arrangement of interconnected voids, irregular pore openings, and rough surface features, suggesting structural modifications associated with the carbonization and activation processes. At 1,000× magnification, the developed PSAC filter displayed a sponge-like morphology with numerous surface cavities and interconnected channels, indicating a more developed visible porous structure compared with the raw and commercially available activated carbon filters. The observed morphological characteristics of the developed PSAC filter suggest that the activation process contributed to the formation of surface irregularities and accessible pore structures, which may enhance the diffusion and interaction of gaseous pollutants with the carbonaceous adsorbent [25]. The interconnected voids and rough surface morphology may facilitate mass transfer by providing pathways for gas molecules to access internal adsorption sites. Nevertheless, micropores less than 2 nm, which play a critical role in gas-phase adsorption, cannot be directly identified from the SEM micrographs obtained at the investigated magnifications [26]. Therefore, although the SEM observations provide qualitative evidence of morphological development, quantitative characterization of specific surface area, pore volume, and pore size distribution is necessary to establish the relationship between surface morphology and adsorption performance.

The comparative SEM analysis demonstrated distinct morphological differences among the three filter materials. The raw filter exhibited a relatively smooth fibrous structure primarily associated with mechanical particle filtration, whereas the commercially available activated carbon filter displayed partial carbon coverage and increased surface roughness. The developed PSAC filter demonstrated more extensive carbon deposition and a visibly heterogeneous porous morphology, suggesting its potential suitability as an alternative carbon-based adsorbent for air filtration applications. However, the extent to which these morphological characteristics contribute to improved gas adsorption efficiency should be further evaluated through adsorption performance testing and quantitative pore structure analysis.

4.2 Energy Dispersive X-ray Spectroscopy (EDS)

Energy-dispersive X-ray spectroscopy (EDS) was conducted in conjunction with scanning electron microscopy (SEM) to investigate the elemental composition and surface characteristics of the filter samples. The analysis provided quantitative information on the distribution of carbon, oxygen, and other trace elements, allowing a comparative assessment of the elemental characteristics of the raw filter material and commercial activated carbon filter. Figure 5(a) presents the EDS spectrum of the raw filter material, indicating that carbon (C) and oxygen (O) were the predominant elements, accounting for 61.96 wt.% (68.46 at.%) and 37.95 wt.% (31.48 at.%), respectively. The substantial proportions of carbon and oxygen are consistent with the elemental composition of organic polymer-based materials commonly employed in conventional air filtration media. Additionally, a trace amount of sodium (Na), corresponding to 0.10 wt.%, was detected, potentially originating from manufacturing additives, processing residues, or surface contamination. The absence of significant inorganic constituents suggests that the raw filter primarily consists of carbon- and oxygen-containing materials. These findings are consistent with the SEM observations of the fibrous morphology, suggesting that the raw filter is predominantly designed for mechanical particulate

filtration rather than gas-phase adsorption. However, elemental composition alone cannot establish the adsorption capability of the material, which requires further evaluation of its surface area, pore structure, and adsorption performance.

In contrast, the EDS analysis of the commercial activated carbon filter revealed a higher carbon concentration of 76.28 wt.% (81.27 at.%), accompanied by an oxygen content of 22.97 wt.% (18.38 at.%). The increased carbon concentration compared with those of the raw filter is consistent with the incorporation of a carbon-rich adsorbent within the commercial filtration medium. Minor concentrations of calcium (Ca) and sodium (Na), corresponding to 0.27 wt.% and 0.48 wt.%, respectively, were also identified. These inorganic constituents may be attributed to residual mineral impurities in the carbon precursor or chemical additives introduced during activation and filter manufacturing [27]. Furthermore, the detected oxygen may be associated with oxygen-containing surface functional groups, which can influence the surface polarity and adsorption interactions of activated carbon with specific gaseous pollutants. Nevertheless, EDS analysis does not directly identify the chemical bonding states or functional groups present on the carbon surface. Compared with the raw filter material, the commercial activated carbon filter exhibited a higher carbon-to-oxygen ratio, indicating a more carbon-rich composition that is consistent with the presence of activated carbon. These findings complement the SEM morphological observations and provide supporting evidence of differences in material composition between the conventional and commercial activated carbon filters [28]. The SEM–EDS results demonstrate distinct differences in the elemental composition of the investigated filter materials, particularly in terms of carbon concentration and the presence of minor inorganic constituents. Although the higher carbon content of the commercial activated carbon filter is consistent with its intended adsorptive function, its actual gas adsorption performance depends on additional physicochemical characteristics, including specific surface area, micropore volume, pore size distribution, and surface functional groups.

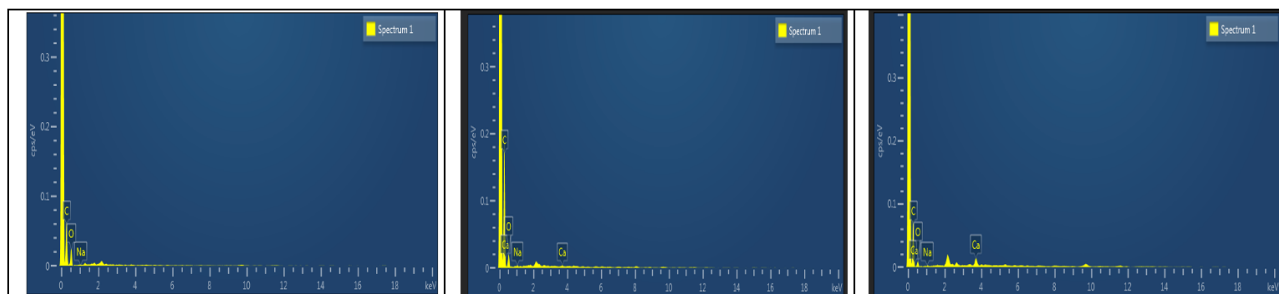


Fig. 5. EDS results for (a) raw material filter; (b) commercial activated carbon filter; (c) palm shell activated carbon

The energy-dispersive X-ray spectroscopy (EDS) analysis of the palm shell activated carbon (PSAC) filter, as presented in Figure 5(c), reveals a carbon-dominated elemental composition, with carbon and oxygen identified as the major constituents. Quantitative analysis indicates that carbon accounts for 75.87 wt% (82.49 at%), followed by oxygen at 19.34 wt% (15.78 at%). The relatively high carbon content is consistent with the successful carbonization and activation of palm shell biomass. Additionally, calcium (Ca) was detected at 4.13 wt%, exceeding the concentration observed in the commercial activated carbon filter. The presence of calcium may be attributed to naturally occurring inorganic minerals and residual ash constituents in the palm shell biomass. Meanwhile, a relatively low sodium (Na) concentration of 0.66 wt% was identified, potentially originating from intrinsic mineral constituents or residual chemicals introduced during the activation process [29]. The detected oxygen content suggests the possible presence of oxygen-containing surface functional groups, which may contribute to enhanced interactions between the activated carbon surface and

polar gaseous pollutants. However, further surface chemical characterization is required to confirm the nature of these functional groups. Despite the presence of minor inorganic constituents, the PSAC filter maintains a predominantly carbonaceous composition, consistent with the characteristics of biomass-derived activated carbon [30]. The EDS findings support the formation of a carbon-rich PSAC material and its presence within the filter structure. Compared with the raw and commercial filters, the PSAC filter exhibits substantial carbon content with relatively low concentrations of inorganic elements, indicating its potential suitability as a sustainable adsorbent for air-conditioning filtration applications. Nevertheless, its filtration effectiveness should be further validated through gas adsorption and air purification performance assessments.

5. Conclusion

In conclusion, this study successfully developed an air-conditioning filter incorporating palm shell activated carbon (PSAC) through carbonization, chemical activation, and filter fabrication processes. The morphological and elemental characteristics of the developed filter were evaluated using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). SEM analysis revealed a well-developed porous structure characterized by rough surfaces and interconnected pores, with more pronounced pore development compared to the raw and commercial activated carbon filters, indicating its potential for adsorption applications. EDS analysis demonstrated a carbon-dominant composition, comprising 75.87 wt% carbon (82.49 at%) and 19.34 wt% oxygen (15.78 at%), confirming the formation of a carbon-rich material from palm shell biomass. Minor elemental constituents, including calcium (4.13 wt%) and sodium (0.66 wt%), were also detected, potentially originating from naturally occurring minerals and residual activating agents. Overall, the findings demonstrate the feasibility of converting palm shell biomass into activated carbon for air-conditioning filter applications. The developed PSAC filter exhibits promising morphological and elemental characteristics, highlighting its potential as a sustainable and environmentally friendly filtration material. However, further investigations into gas adsorption capacity, filtration efficiency, and airflow resistance are required to validate its practical performance in air-conditioning systems.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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