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IDENTIFYING THE EFFECT OF CARBONIZATION TEMPERATURE ON THE POROUS STRUCTURE AND ELECTRICAL CONDUCTIVITY OF ACTIVATED CARBON DERIVED FROM QUAIL EGGSHELL

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The object of this study is to evaluate the potential of quail eggshells as a raw material for producing porous and electrically conductive activated carbon by focusing on the effect of carbonization temperature. The main problem solved is the lack of utilization of quail eggshell waste, despite its unique microporous structure and rich mineral and organic content. This underutilized waste, often discarded, represents an opportunity to align sustainable practices with the development of advanced materials for adsorbent and energy applications.

The results showed that the activated carbon produced at a carbonization temperature of 400 °C had superior properties compared to higher temperatures (500 °C and 600 °C), with the highest surface area and electrical conductivity. FTIR characterization identified important functional groups such as O-H, C=O, C=C, and CaO, which support the formation of the carbon framework and contribute to the stability and functionality of the material. XRD patterns confirmed the hexagonal carbon structure, a desirable feature for maintaining structural integrity in demanding applications. SEM revealed irregular morphologies, while BET analysis showed a combination of micropores and mesopores. Under optimal carbonization conditions, activated carbon produced at 400 °C offers a combination of structural and conductive properties. It achieved a specific surface area of 296.875 m^2/g, indicating excellent porosity for adsorption applications. Additionally, the material exhibited an electrical conductivity of 1.62×10^{-2} S/cm, which is suitable for energy storage devices such as supercapacitors and batteries. The decrease in these properties at higher carbonization temperatures highlights the importance of optimizing synthesis parameters to achieve desired outcomes

These structural and conductive properties make the material suitable for advanced applications in environmental remediation, renewable energy, and waste management. By converting quail eggshells into high-value activated carbon, the study demonstrates a feasible approach to reducing waste while contributing to eco-friendly material development. This study proves that quail eggshells can be effectively utilized, adding value to organic waste while increasing its economic viability.

Keywords: activated carbon, quail eggshells, carbonization temperature, structural and porous characterization, electrically conductive properties

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1. Introduction

Activated carbon, a porous material of great significance, is widely used in various applications such as an adsorbent for chemicals and gases, an electrode material in supercapacitors, and a supporting material for catalysts [1]. Activated carbons are carbon-rich materials characterized by a highly porous structure, giving them a substantial specific surface area that enhances surface interaction and diffusion within their structures [2]. The porous structure, particularly pore size and distribution, is essential in determining the function and suitability for specific applications. These characteristics are influenced by the choice of raw materials and production methods, making it essential to understand the factors that affect activated carbon properties.

In recent years, interest has grown in developing cost-effective methods for producing activated carbon. Commercial production remains costly due to the high expenses associated with equipment and maintenance, particularly when using traditional natural precursors like wood and coal. Consequently, a significant amount of research has focused on identifying affordable and eco-friendly alternatives for activated carbon production. While biomass resources are widely used for activated carbon production, the focus has predominantly been on lignocellulosic materials, leaving protein-based sources relatively unexplored. Eggshells, especially as an agricultural byproduct, present a promising protein-based feedstock for activated carbon due to their natural porous structure and composition, offering a low-cost, sustainable alternative for activated carbon application [3].

Eggshells are composed of approximately 94 % calcium carbonate ($CaCO_3$), 1 % magnesium carbonate ($MgCO_3$), 1 % calcium phosphate ($Ca_3(PO_4)_2$), and 4 % organic matter. Each eggshell is estimated to contain between 7,000 and 17,000 pores [4], which makes them prospective for use in activated carbon production. Numerous studies have explored the utilization of eggshell waste for the production of activated carbon, including investigations into the synthesis of activated carbon from chicken, duck, and ostrich eggshells [5]. However, quail eggshells, as a readily available and underutilized waste resource, have not been extensively studied in this context. Exploring quail eggshells as activated carbon is significant, as protein-rich materials like these may offer unique structural and chemical properties advantageous for high-performance activated carbon. Considering the significance of identifying sustainable raw materials for activated carbon production, exploring the potential of quail eggshells aligns well with environmental and technological objectives. By converting this underutilized resource into activated carbon, the study advances sustainable materials research, meeting current needs in environmental technologies, renewable energy solutions, and waste utilization efforts.

Therefore, studies devoted to the development of activated carbon from alternative and sustainable sources like eggshell waste are scientifically relevant. By focusing on underutilized protein-based sources, this field not only diversifies the raw materials available for activated carbon synthesis but also aligns with sustainability goals. These efforts are crucial in meeting the increasing demands of modern environmental and energy applications.

2. Literature review and problem statement

Activated carbon is widely applied carbonaceous material with high porosity and a surface area between 250–2,000 m^2/g, making it suitable for adsorbent and energy applications [6]. Measuring porous and electrical properties is crucial to assess its suitability for industrial uses such as pollutant removal, gas storage, and energy devices like batteries and supercapacitors. Porosity determines adsorption efficiency, while electrical conductivity affects electrochemical performance, optimizing applications in sustainable technologies.

Mostly commercial activated carbon is derived from non-renewable sources such as coal and wood. A study [7] demonstrates that activated carbon derived from coal has a high carbon content with minimal residue. However, its widespread application is limited due to high production costs and environmental concerns. These challenges arise from the reliance on non-renewable sources and the expensive equipment required for processing. A way to address these difficulties is by exploring renewable and cost-effective alternatives such as biomass-derived materials. Therefore, low-cost and renewable materials like agricultural and household biowaste are increasingly explored as sustainable sources for activated carbon production, offering both environmental and economic benefits.

Eggshell waste, which is abundant and largely untapped, offers a promising alternative due to its rich calcium carbonate ($CaCO_3$) and is naturally porous. By optimizing its structure through carbonization and activation, eggshell-based activated carbon could provide effective, sustainable solutions for various applications. In the work [8], the use of carbonized chicken eggshell waste was explored for its CO_2 adsorption potential, proving effective due to its calcium carbonate content and porous structure. However, it did not address critical factors such as the influence of carbonization temperature on the material's functional groups or crystal structure, leaving a gap in understanding its comprehensive properties. The same research in the paper [9] investigated the effectiveness of chicken eggshell-derived activated carbon for carbon monoxide (CO) adsorption. But this study also did not address how different carbonization temperatures affect its porous structure, which is crucial for optimizing its performance in various applications.

In [10], porous carbon from eggshells with a surface area of 626 m^2/g and strong adsorption capacities for organic pollutants like sulfamethoxazole and methyl orange was produced, showcasing eggshell waste as a high-performance activated carbon source. However, these studies did not explore the impact of carbonization temperature on the material's pore distribution. The same study was also reported by [11], activated carbon from country eggshells showed a 73 % degradation efficiency for methylene blue. XRD results revealed a crystalline hexagonal graphite structure, while FT-IR identified specific functional groups. SEM images displayed an irregular, amorphous carbon structure, with an average particle size of 159 nm. But this study did not address the specific surface area and pore distribution of the activated carbon, leaving these as critical gaps for further investigation. The work [12] investigates the use of waste chicken eggshell as an adsorbent for removing cadmium (Cd) from aqueous solutions. The results showed that the ability to remove cadmium reached up to 73 %. However, none of these studies provide comprehensive insights into the relationship between carbonization temperature conditions and porous properties. Addressing these gaps is essential for expanding the applicability of activated carbon derived from eggshells in adsorbent fields.

In [13], the eggshells, processed at 600 °C and 900 °C, showed effective capacitance in capacitors and performed well as battery anodes, achieving around 280 mAh g^{-1}. The results show a well-developed structure at a carbonization temperature of 900 °C, which retained over 84 % of its capacity. However, the study did not address the electrical conductivity of the activated carbon, which is critical for understanding its efficiency in electron trans-

fer and overall electrochemical performance. The same study also reported in [14] that hen eggshells exhibited higher specific capacitance (155.8 F/g) and lower impedance. These results suggest that hen eggshells are promising alternatives for electrochemical devices. But this study did not address the effect of carbonization temperature conditions on the electrically conductive properties. Evaluating conductivity would enhance the material's suitability for electronic and energy devices.

Previous research highlights that in the production of activated carbon, factors such as carbonization temperature and the choice of activating agent play a pivotal role. These factors significantly influence the material's porosity and specific surface area, which directly affect its overall functionality and suitability for various applications. The production of activated carbon from eggshells involves two main processes: carbonization and activation, during carbonization, the raw eggshell material is heated in an inert atmosphere at temperatures ranging from 400–800 °C [15]. This process removes non-carbon compounds, leaving behind a carbon-rich structure [16]. Activation, which can be physical or chemical, further enhances the material's porosity and surface area. Physical activation uses high-temperature gases like CO_2 or steam, while chemical activation involves treating the material with agents such as H_3PO_4, H_2SO_4, HNO_3, NaOH, KOH, Na_2CO_3, K_2CO_3, $AlCl_3$, and $ZnCl_2$, under controlled conditions, optimizing its adsorptive and electrochemical properties [17]. Among these, regarding the study of [18], KOH is preferred as an activating agent due to its superior ability to enhance porosity and surface area. The results indicate that KOH activation achieves a specific surface area of 2,547 m^2/g compared to K_2CO_3 and $KHCO_3$ activation, which yielded 1,625 m^2/g and 1,457 m^2/g, respectively. However, unresolved issues remain regarding the optimization of carbonization conditions and the efficient use of KOH as an activator in eggshell-derived activated carbon production. Addressing these gaps is essential to maximize the material's functional properties and ensure cost-effective, sustainable production processes.

Based on previous studies, it is evident that much work has been dedicated to the synthesis and characterization of activated carbon from chicken and duck eggshells. However, studies specifically examining quail eggshells remain limited. This research seeks to address this gap by optimizing carbonization temperatures for quail eggshell-derived activated carbon to enhance its porosity, surface area, and electrical conductivity. This approach not only utilizes underexplored protein-based waste but aligns with sustainable material development goals, as quail eggshell-derived activated carbon could provide a viable, eco-friendly alternative to conventional carbon sources.

3. The aim and objectives of the study

The aim of the study is to evaluate the effect of carbonization temperature on the porous and electrically conductive properties of activated carbon derived from quail eggshells. The study focuses on determining the optimal conditions for synthesizing activated carbon with superior characteristics for potential applications.

To achieve this aim, the following objectives are accomplished:

– investigating the effect of carbonization temperature on the characteristics of its functional groups of synthesized activated carbon from quail eggshells using FTIR analysis;

– investigating the effect of carbonization temperature on the characteristics of the crystal structure, crystallite size, and crystallinity of synthesized activated carbon from quail eggshells using XRD analysis;

– investigating the effect of carbonization temperature on the morphological structure of synthesized activated carbon from quail eggshells using SEM analysis;

– investigating the effect of carbonization temperature on the surface area, pore size, and pore distribution of synthesized activated carbon from quail eggshells using BET analysis;

– investigating the effect of carbonization temperature on the electrical properties of synthesized activated carbon from quail eggshell using electrical conductivity measurement.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of our research is to evaluate the porous structure and electrical conductivity properties of activated carbon synthesized from quail eggshells during the carbonization process, with the goal of optimizing carbonization temperature conditions to enhance the activated carbon's performance for advanced future applications.

The research hypothesis assumes that varying carbonization temperatures significantly influence the structural, morphological, porous structure, and electrical conductivity properties of activated carbon derived from quail eggshells, thereby affecting its suitability for advanced applications.

The assumption adopted in the research process is that carbonization effects are consistent across the selected temperature ranges, ensuring reliable comparisons between samples.

The simplification accepted in the research process concerns standardized activation conditions, such as consistent KOH concentration and fixed carbonization duration, to focus on the influence of temperature variation.

4. 2. Preparation of activated carbon from quail eggshell

The production process of activated carbon from quail eggshells is shown in Fig. 1. Quail eggshell waste was sourced from local quail farmers in Jember Regency, East Java, Indonesia. The eggshells were collected from cracked or damaged eggs during the harvesting process. After separating the eggshells from their contents, they were thoroughly washed with running water and sun-dried. The dried eggshells were then ground into a fine powder using a blender.

The quail eggshell powder was activated using a 20 % (w/v) KOH solution with a ratio of 1:4 (w/w) for 24 hours. Following activation, the eggshells were filtered and oven-dried at 110 °C for 24 hours. Carbonization was carried out in a furnace at temperatures of 400 °C, 500 °C, and 600 °C for 2 hours. The resulting activated carbon from quail eggshells was then characterized using FTIR, XRD, SEM, and BET analysis. Additionally, the electrical conductivity was also measured.

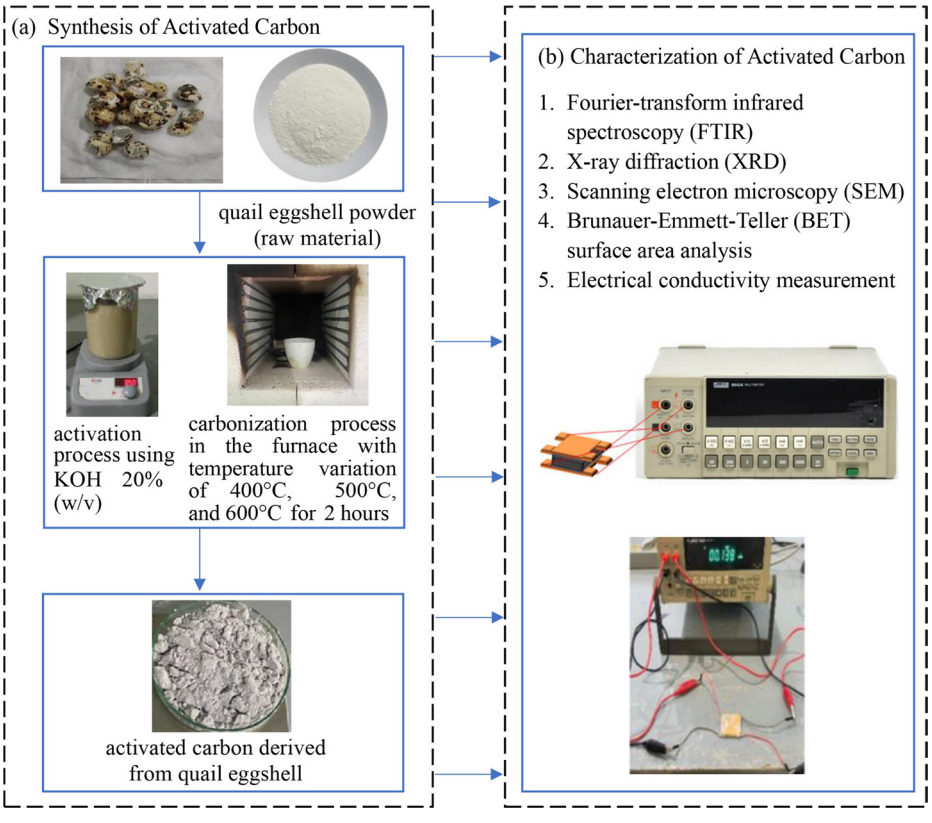


Fig. 1. Scheme of preparation of activated carbon derived from quail eggshell

4. 3. Characterization of activated carbon from quail eggshell

4. 3. 1. Fourier-transform infrared spectroscopy (FTIR) analysis

FTIR spectroscopy (Routine Spectrometers) was used to identify the functional groups present in the activated carbon. The activated carbon analysis using FTIR was performed by mixing 0.2 mg activated carbon with 2 mg KBr and forming pellets. The pellets of the sample are fed to the FTIR instrument with λ 4,000 to 500 cm^{-1}.

4. 3. 2. X-ray diffraction (XRD) analysis

Samples were prepared as much as 0.3 grams and then scanned by XRD apparatus (PANanalytical, type: E'xpert Pro) operating with a Cu Kα (λ=1.54060 Å) radioactive source. The XRD patterns were analyzed with MDI Jade software and compared with the International Center Diffraction Database (ICCD) in the Powder Diffraction File (PDF). The crystallite size (D) was calculated using the Debye-Scherrer equation [19]Linear Straight-Line Model, Munshi Scherrer Model, Uniform Deformation Model, Uniform Stress Deformation Model, Uniform Deformation Energy Density Model, Size Strain Model, Halder Wagner Model, and Sahadat Scherrer Model were engaged to estimate crystallite size as well as strain, stress, and energy density from few models. All the models were evaluated with their merits and demerits along with usefulness. All the mentioned models showed acceptable results as the crystallite size ranges were from 22 to 77 nm except Linear Straight-Line Model (revealed invalid results for all the synthesized samples:

$$D = \frac{k\lambda}{\beta\cos\theta}, \quad (1)$$

where the Scherrer constant (k) is 0.9, β is the full width at half maximum (FWHM), and θ is the diffraction angle. Crystallinity was determined by comparing the area of the crystalline peaks with the total area of both crystalline and amorphous regions.

4. 3. 3. Scanning electron microscopy (SEM) analysis

The morphology of the activated carbon was characterized using SEM-EDX (FEI, JEOL-JSM-6510LA). SEM analysis of activated carbon is done by freezing the sample powder over the aluminum to dry. Then, using Polaron, sprinkle the sample with gold for 30 seconds. The results are displayed in stereoscans. SEM was used to investigate the microscopic structure and surface morphology of activated carbon.

4. 3. 4. Brunauer-Emmett-Teller (BET) analysis

The Brunauer-Emmett-Teller (BET) method was conducted using a Quantachrome NovaWin instrument. The adsorption isotherms were conducted from the adsorption of nitrogen at 77.350 K. The activated carbon samples were degassed with nitrogen for four hours to determine their BET surface area. The pore size distribution was derived from the adsorption and desorption isotherms using the Barrett-Joyner-Halenda (BJH) method.

4. 3. 5. Electrical conductivity analysis

Samples resulting from the carbonization process with temperature variation of 400 °C, 500 °C, and 600 °C were measured using a Fluke 8842A Digital Multimeter, employing the four-point probe method. The electrical conductivity of activated carbon from quail eggshells can be determined from the resistance measured on the 8842A Fluke Multime-

ter, which is then calculated using the equation below [20] notably in electronics, biomedicine and food industry. One promising strategy involves the integration of electrically conductive nanostructures into a polymeric matrix to fabricate composite materials. However, achieving uniform through-plane electrical conductivity remains a challenge due to the preferential alignment of carbon nanostructures in the in-plane direction. Herein, we report the development of electrically conductive chitosan (CS):

$$\sigma = \frac{L}{AR}, \quad (2)$$

where σ was the electrical conductivity (S/cm), R was the electrical resistance (Ω), L was the distance between the plates (cm), and A was the surface area (cm^2).

5. Results of investigating the effect of carbonization temperature on the characteristics of porous and electrically conductive activated carbon from quail eggshells

5. 1. Effect of carbonization temperature on functional groups (FTIR analysis)

The FTIR spectra of activated carbon derived from quail eggshells, carbonized at temperatures of 400 °C, 500 °C, and 600 °C (Fig. 2), reveal the presence of hydroxyl groups. Absorption peaks at wavenumbers 3,641 cm^{-1}, 3,643 cm^{-1}, and 2,515 cm^{-1} correspond to O-H stretching vibrations.

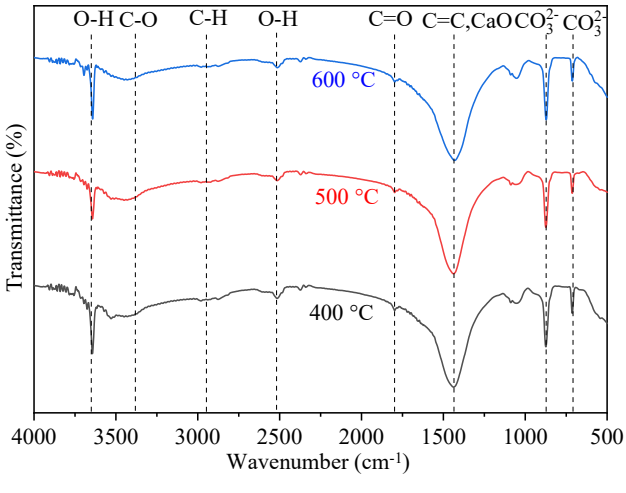


Fig. 2. FTIR spectra of activated carbon from quail eggshell at various carbonization temperatures

At wavenumbers 3,421 cm^{-1}, 3,429 cm^{-1}, and 3,448 cm^{-1}, C-O asymmetric stretching groups are observed. C-H bending vibrations appear at peaks around 2,924 cm^{-1}, 2,875 cm^{-1}, and 2,924 cm^{-1}, suggesting the presence of organic layers from amino acids on the eggshells. Peaks around 1,797 cm^{-1} in all activated carbon samples indicate C=O (carbonyl) groups due to C=O stretching bonds. The broadest peaks at wavenumbers around 1,436 cm^{-1} and 1,431 cm^{-1} suggest the presence of C=C and CaO functional groups, indicating that the samples contain both carbon and calcium oxide. Peaks at wavenumbers around 873.75 cm^{-1}, 871.82 cm^{-1}, 713 cm^{-1}, and 711 cm^{-1} are attributed to carbonate $(CO_3)^{2-}$ functional groups. The presence of $(CO_3)^{2-}$ groups originates from $CaCO_3$, which is not fully decomposed at a carbonization temperature of 400 °C. At a carbonization temperature of 600 °C, $(CO_3)^{2-}$ is still present because the carbonate component will only completely decompose into CaO when the temperature exceeds 700 °C.

5. 2. Effect of carbonization temperature on crystal structure, crystallite size, and crystallinity (XRD analysis)

The XRD pattern of activated carbon derived from quail eggshells is shown in Fig. 3. The XRD peaks for activated carbon carbonized at temperatures of 400 °C, 500 °C, and 600 °C are consistent with calcium carbonate ($CaCO_3$) in the form of calcite, with hkl 104 reflections appearing at 2 angles of 29.46°, 29.48°, and 29.44°, respectively. The activated carbon samples are predominantly composed of calcium carbonate ($CaCO_3$) and calcium hydroxide ($Ca(OH)_2$). The $CaCO_3$ peaks are observed at 2θ=23.12°, 29.47°, 36.05°, 39.50°, 43.24°, 47.59°, and 48.58°, while the $Ca(OH)_2$ peaks are located at 2θ=18.12°, 28.71°, 34.16°, 47.17°, 50.86°, and 54.38°.

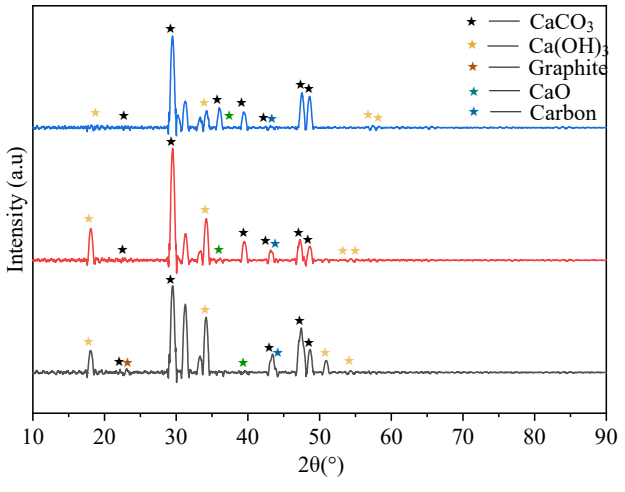


Fig. 3. Diffractogram of activated carbon derived from quail eggshell at various carbonization temperatures

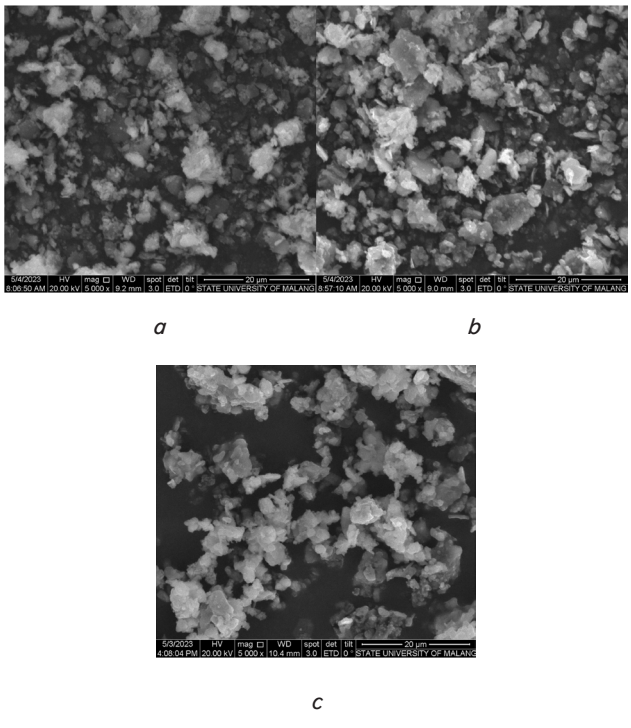
The content of calcium oxide (CaO), carbon, and graphite in the activated carbon from quail eggshells is relatively low. The XRD peak for calcium oxide (CaO) appears at 2θ=37.35°. The peak for graphite carbon is found at 2θ=26.38°, with a weak peak at 2θ=43.93° indicating amorphous carbon. The crystal structure of the carbon in the activated carbon, across the carbonization temperatures of 400 °C, 500 °C, and 600 °C, is hexagonal. This hexagonal structure is characterized by lattice parameters $a=b$=2.552 Å, c=43.245 Å, with α=β=90° and γ=120°. The hexagonal crystal structure is observed at peaks of 2θ=43.91°, 43.92°, and 43.93°, respectively.

The crystal size of the activated carbon increases with higher carbonization temperatures. The crystal sizes at carbonization temperatures of 400 °C, 500 °C, and 600 °C are 52.65 nm, 55.88 nm, and 58.67 nm, respectively. Additionally, the increase in carbonization temperature results in higher crystallinity of the activated carbon. The crystallinity at these temperatures is 54.38 %, 58.90 %, and 58.99 %, respectively.

5. 3. Effect of carbonization temperature on morphological structure (SEM analysis)

SEM was used to observe the surface morphology of activated carbon derived from quail eggshells. Fig. 4 displays the SEM micrographs of activated carbon prepared at

various carbonization temperatures (i.e., 400 °C, 500 °C, and 600 °C). The surface morphology of the activated carbon appears irregular, rough, porous, and granular. At carbonization temperatures of 400 °C and 500 °C, the activated carbon still exhibits the presence of impurities scattered on the surface. The pore distribution on the activated carbon at these temperatures is only slightly visible, as the quail eggshells have undergone activation using a KOH activator.



a *b* *c*

Fig. 4. SEM images of activated carbon derived from quail eggshell at carbonization temperature: *a* — 400 °C; *b* — 500 °C; *c* — 600 °C

At a carbonization temperature of 600 °C, the surface of the activated carbon appears more homogeneous compared to the carbonized samples at 400 °C and 500 °C. The particle sizes on the surface of the activated carbon are as follows: 0.71–10.16 µm for 400 °C, 0.74–8.93 µm for 500 °C, and 0.73–7.57 µm for 600 °C. This indicates that as the carbonization temperature increases, the particle size on the surface of the activated carbon becomes smaller and more homogeneous.

5. 4. Effect of carbonization temperature on surface area, pore size, and pore distribution (BET Analysis)

Table 1 shows the effect of different carbonization temperatures on the surface area, pore size, and pore volume of activated carbon produced in this study. The largest surface area, reaching 296.875 m^2/g, was produced by activated carbon from quail eggshells carbonized at 400 °C. The carbonization temperature of 500 °C resulted in a surface area of 12.442 m^2/g, while carbonization at 600 °C produced a surface area of 13.558 m^2/g. These results indicate that the carbonization temperature significantly influences the surface area of the activated carbon derived from quail eggshells.

The total pore volumes of the prepared activated carbons decrease by 0.250 to 0.040, respectively, from 400 °C to 600 °C of the carbonization temperature. Meanwhile the pore size of activated carbon increases with increasing the carbonization temperature. The increase in pore size with carbonization temperature, from 15.624 Å at 400 °C to 16.957 Å at 600 °C, reflects a shift towards the formation of larger pores, which could be a result of the material undergoing structural rearrangement and expansion at higher temperatures. While the larger pores may still allow for certain types of adsorptions, the overall surface area and total pore volume have been reduced, indicating that higher temperatures lead to a decrease in the material's overall adsorption capacity due to the loss of smaller, more numerous pores.

Table 1

The surface area test results of activated carbon from quail eggshells

Carbonization temperature (°C)	Surface area (m^2/g)	Pore size (Å)	Pore volume (cc/g)
400	296.875	15.624	0.250
500	12.442	15.066	0.044
600	13.558	16.957	0.040

The porous properties of activated carbon from quail eggshells can be analyzed using nitrogen adsorption-desorption at a temperature of 77.350 K, resulting in an isotherm curve as shown in Fig. 5. These isotherms reveal that the carbonized samples at temperatures of 400 °C, 500 °C, and 600 °C exhibit a type III isotherm curve according to the IUPAC classification. The increase in activation temperature from 400 °C to 600 °C led to changes in the porous structure that reduced nitrogen adsorption, with 400 °C showing higher adsorption compared to 500 °C and 600 °C, likely due to the formation of smaller and more regular pores at the lower temperature.

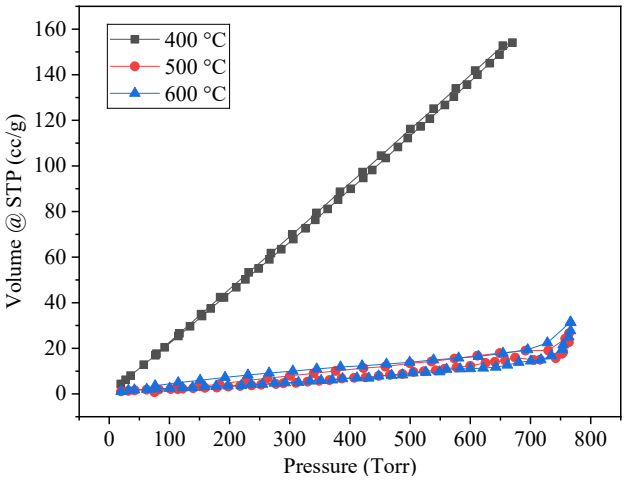


Fig. 5. BET analysis of the nitrogen adsorption-desorption isotherm curve of activated carbon derived from quail eggshell at carbonization temperature: A — 400 °C; B — 500 °C; C — 600 °C

The pore size distribution of activated carbon derived from quail eggshells can be determined using the BJH (Barrett-Joyner-Halenda) method. Fig. 6 illustrates a prominent peak around a pore diameter greater than 20 Å, with a gradual slope extending to a pore diameter between 20 Å and 70 Å. This suggests that the activated carbon derived from quail eggshells possesses a combination of micropores and mesopores, indicating a diverse pore structure.

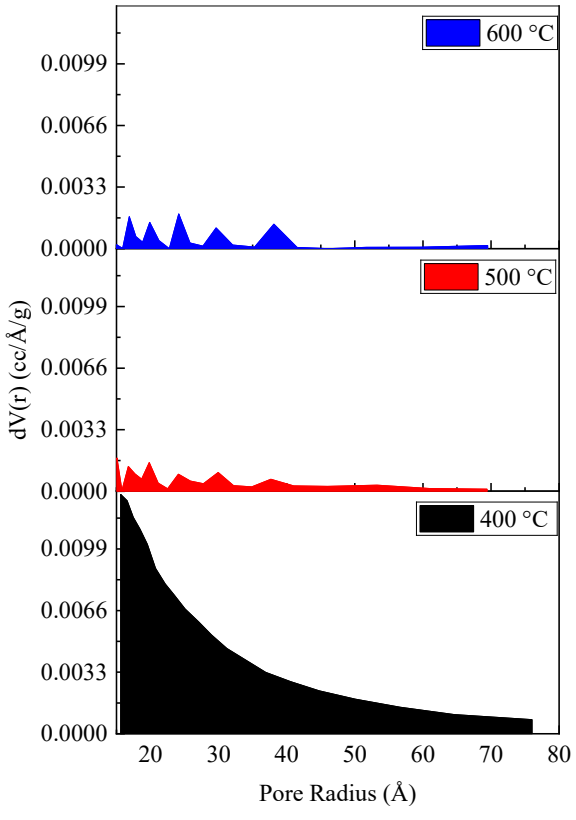


Fig. 6. Pore distribution of activated carbon derived from quail eggshell at various carbonization temperatures

This distribution pattern from these results suggests that the activated carbon from quail eggshells was not limited to just micropores, but also contains mesopores. The combination of these two types of pores, micropores and mesopores, suggests a versatile porous structure, offering a broad surface area for adsorption. At a carbonization temperature of 400 °C, the activated carbon derived from quail eggshells likely has a pore structure predominantly consisting of micropores (≤20 Å) and small mesopores (20–50 Å). The surface area at this temperature may still be relatively higher compared to higher carbonization temperatures. At carbonization temperatures of 500 °C and 600 °C, the pore structure becomes more balanced, with both micropores and more pronounced mesopores causing pore widening and collapse of smaller micropores.

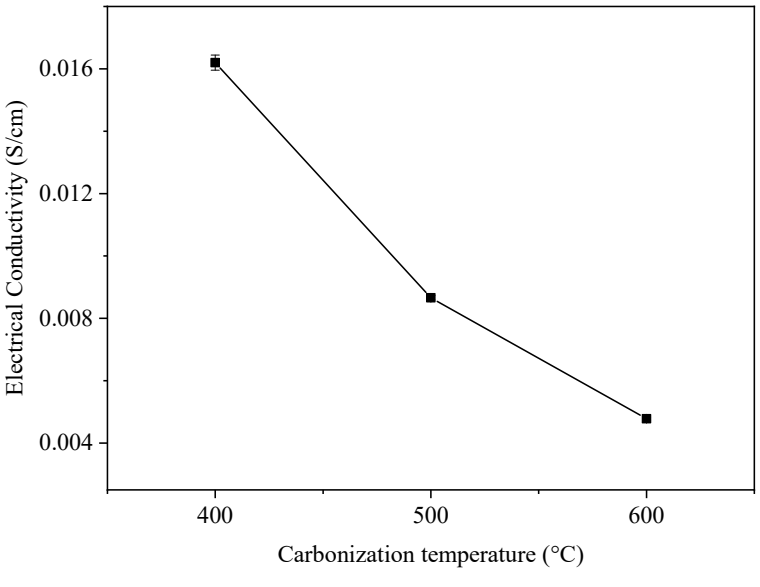


Fig. 7. Electrical conductivity of activated carbon derived from quail eggshell at various carbonization temperatures

5. 5. Effect of carbonization temperature on electrical properties (electrical conductivity measurements)

Electrical conductivity can be defined as an intrinsic property used to determine a material's ability to conduct electricity. The electrical conductivity of activated carbon from quail eggshells is presented in Fig. 7. The conductivity values for the activated carbon range from 1.62×10^{-2} S/cm to 4.78×10^{-3} S/cm. The highest electrical conductivity is observed in the activated carbon carbonized at 400 °C for 2 hours, with a value of ($1.62\times10^{-2}\pm2.43\times10^{-4}$) S/cm. The conductivity decreases when carbonization is performed at 500 °C for 2 hours, yielding ($8.66\times10^{-3}\pm6.92\times10^{-5}$) S/cm. At a carbonization temperature of 600 °C, the electrical conductivity is ($4.78\times10^{-3}\pm5.37\times10^{-5}$) S/cm.

As a correlation between the results, the increase in surface area and changes in the pore structure of activated carbon derived from quail eggshells have a significant impact on its electrical conductivity. The increase in the carbonization temperature of activated carbon from quail eggshells indicates a large number of micropores that facilitate the formation of an electric double layer on the electrode surface. However, as the carbonization temperature increases to 600 °C, there is a decrease in surface area, which may reduce charge storage capacity and electrical conductivity.

6. Discussion of the results of investigating the characteristics of porous and electrically conductive activated carbon from quail eggshells

The internal structure of the activated carbon is considered to be the most important factor, because it directly influences the material's adsorption capacity, surface area, and overall performance in various applications. To characterize the surface groups on activated carbon derived from quail eggshell at carbonization temperatures of 400 °C, 500 °C and 600 °C, Fourier transform infrared (FTIR) spectra were recorded. According to FTIR spectra (Fig. 2), the functional groups present in the activated carbon from quail eggshells in this study include O-H stretching, C-O asymmetric, C-H bending, C=O stretching (carboxyl group), CaO, C=C, and $(CO_3)^{2-}$. Based on these functional groups, the presence of C=C and CaO groups is characteristic of activated carbon from eggshells. These bonds indicate the characteristics of the material possessed by activated carbon from quail eggshells.

FTIR analysis of activated carbon at various carbonization temperatures shows that higher temperatures cause upshifts in wavenumbers and reduced transmittance rates. The functional groups with the lowest transmittance values are found in the C=C and CaO groups, followed by the $(CO_3)^{2-}$ group. The low transmittance values for C=C, CaO, and $(CO_3)^{2-}$ are likely due to stronger interactions between atoms within these groups. Additionally, these low transmittance values indicate high absorption of infrared radiation frequencies. As the number of molecules within the material increases, the number of absorbing units also increases, resulting in less infrared radiation being transmitted.

Higher temperatures usually increase the bond strength between atoms within the carbon structure, particularly in groups like C=C, CaO, and $(CO_3)^{2-}$. Stronger bonds vibrate at higher frequencies, leading to an upshift in wavenumbers, which appears as a shift to the right in the FTIR spectrum. This upshift occurs because the wavenumber is directly proportional to the vibrational frequency of the bonds; as the bond strength increases, so does the vibrational frequency and, consequently, the wavenumber.

The reduction in band intensity supports the notion of bond cleavage, particularly of C=C stretching bonds, indicating a progressive elimination of hydrogen functional groups. This leads to enlarged pore sizes as hydrocarbons and surface molecules break down. The decreased transmittance of C=C, CaO, and $(CO_3)^{2-}$ bands is likely due to stronger interactions between atoms. Additionally, reduced band intensity suggests increased absorption of high-frequency infrared light, implying that more molecules present in the material result in more absorption units and fewer infrared light frequencies transmitted.

The XRD analysis reveals that the activated carbon derived from quail eggshell has low levels of calcium oxide (CaO), carbon, and graphite (Fig. 3). The CaO peak and the graphite peak align with previous studies [21], indicating partial crystallinity. The presence of an amorphous carbon peak at $2\theta=43.93^{\circ}$ supports the notion that higher temperatures (900–1000 °C) optimize CaO formation, while lower temperatures favor calcium carbonate ($CaCO_3$) phases. These results emphasize that achieving desired phases in activated carbon from quail eggshells requires careful temperature control, as lower carbonization temperatures may not fully decompose $CaCO_3$ into CaO, impacting the carbon's structural and functional properties.

The crystal structure obtained in the activated carbon from quail eggshells belongs to the hexagonal phase. This occurs because activated carbon is composed of carbon bonded covalently in a hexagonal lattice. Additionally, the research results show that higher carbonization temperatures result in increased crystal size. Crystal size based on the Debye-Scherrer equation is influenced by the Full Width at Half Maximum (FWHM); if the FWHM value decreases, the obtained crystal size increases. Moreover, crystal size increases due to agglomeration or the joining of several crystal particles into larger crystal particles at higher carbonization temperatures.

As for crystallinity, it is calculated to determine the number of crystals contained in a material. It is found that higher carbonization temperatures lead to higher values of activated carbon crystallinity from quail eggshells. The increasing carbonization temperature results in a more orderly arrangement of atoms in activated carbon, leading to higher crystallinity values. This indicates that the arrangement of carbon atoms becomes more regular, approaching the graphite crystal structure where carbon atoms form a hexagonal lattice. Higher crystallinity is associated with improved electrical conductivity. Therefore, activated carbon with elevated crystallinity can serve as an ideal material for the gas diffusion layer (GDL) in proton exchange membrane fuel cells (PEMFCs), facilitating better electron transport.

Fig. 4, *a*, *b* illustrates that at carbonization temperatures of 400 °C and 500 °C, the surface of quail eggshell-based activated carbon shows impurities scattered across it. This aligns with the theory of carbonization stages, where lignin decomposition occurs at temperatures between 310–500 °C, producing more tar, while the amount of pyroligneous liquid decreases. CO_2 gas decreases, while CO, CH_4, and H_2 gases increase. Comparison with Fig. 4, *a*, *b* shows that the surface of activated carbon at a carbonization temperature of 600 °C (Fig. 4, *c*) appears more homogeneous. This is likely due to the reduction of surface impurities at higher temperatures, resulting in more uniform particle distribution and the emergence of visible pores. Higher carbonization temperatures cause optimal carbon chain breaking, resulting in a more homogeneous activated carbon surface as impurities evaporate. Increasing the carbonization temperature leads to enhanced carbon chain breaking and activated carbon particle size reduction, as evidenced by the smaller and more homogeneous particle size on the activated carbon surface. In addition, the smaller and more homogeneous particle size is due to the diffusion process between particles with small surface areas.

The surface area is one of the most important parameters for determining the quality of activated carbon. A high surface area indicates good-quality activated carbon, as the adsorption capacity is directly related to the surface area. The decrease in the surface area of activated carbon from quail eggshells with increasing carbonization temperature may be due to pore contraction or the deposition of the activator in the pores and cavities of the carbon matrix. Furthermore, increasing the carbonization temperature reduces the BET surface area (Table 1), primarily due to pore blockage by ash deposits. At lower carbonization temperatures, the ash particles remain fine and well-dispersed. However, at higher temperatures, these particles aggregate, leading to more significant pore blockage and a marked decrease in surface area. The trend of results was shown in [22], a similar pore-blocking behavior at elevated temperatures was observed, resulting in a denser, less porous carbon matrix.

Fig. 5 illustrates a type III isotherm curve for all carbonization temperatures (400 °C, 500 °C, and 600 °C) of activated carbon derived from quail eggshells. Type III isotherms represent weak interactions between the adsorbent and adsorbate, suggesting that the material primarily consists of micropores transitioning into mesopores. The observed decrease in nitrogen adsorption at higher carbonization temperatures (500 °C and 600 °C) compared to 400 °C is likely due to pore collapse or enlargement, resulting in less effective pore structures. These results suggest 400 °C as the optimal carbonization temperature for maintaining smaller, more regular pores, and achieving a porous structure suitable for adsorption applications.

In addition to the activation and carbonization processes, the choice of raw materials also influences the resulting surface area of the activated carbon. The surface area of activated carbon from quail eggshells is relatively smaller compared to that of activated carbon made from agricultural waste. This is attributed to the composition of organic material in eggshells, which contains only 4 % organic substances of the total composition. The decrease in surface area with increasing carbonization temperature is associated with an increase in pore size due to the collapse of smaller pores, leading to a higher mesopore volume and consequently reducing the overall surface area. According to the International Union of Pure and Applied Chemistry (IUPAC) classification, the adsorbent pores were classified into three groups: micropores (<20 Å), mesopores (20–500 Å), and macropores (>500 Å) [23]. Fig. 6 shows that the average pore size in activated carbon from quail eggshells is of the micropore type, as the average pore diameter is less than 20 Å. As mentioned in [24], micropores typically make up over 95 % of the total surface area in high-quality activated carbon, which greatly enhances its adsorption capacity. Activated carbon with a high surface area and abundant micropores is more effective for adsorption applications, as these small pores increase the material's ability to trap and hold contaminants or other molecules.

Across the range of carbonization temperatures (400 °C, 500 °C, and 600 °C), a noticeable one-order magnitude decrease in DC electrical conductivity (from 10^{-2} to 10^{-3} S/cm) is seen at higher temperatures. The decrease in electrical conductivity with increasing carbonization temperature (Fig. 7) causes changes in the structural properties of activated carbon, such as reduced surface area and pore volume. At elevated temperatures, pore blockage often occurs due to ash accumulation or the formation of a denser, more compact carbon matrix, reducing the available surface area and disrupting electron transport pathways within the material. Additionally, structural transformations at higher temperatures may reduce the availability of conductive carbon chains and aromatic structures, which contribute to electrical conductivity, resulting in decreased conductivity values.

The observed decrease in electrical conductivity with increasing carbonization temperature may also be influenced by changes in porosity and surface chemistry. Increasing porosity within carbon structures typically leads to a decrease in both thermal and electrical conductivities, as it disrupts continuous conductive pathways. In addition, aggressive chemisorption of oxygen from the air (a process that occurs more readily in activated carbons) can increase electrical resistivity. This might further explain the relatively low electrical conductivity observed in the activated carbon samples, as oxygen chemisorption could inhibit electron movement, adding to the effects of pore blockage and ash accumulation at higher temperatures.

The electrical conductivity results indicate that activated carbon from quail eggshells is a semiconductor material. Semiconductor materials have electrical conductivity values in the range of (10^{-8}–10^{3}) S/cm. Materials suitable for use as electrodes must have relatively high conductivity values. Semiconductor materials are particularly desirable because higher conductivity values enhance the material's ability to conduct electricity. Activated carbon with a high conductivity value demonstrates good electron transfer capabilities. According to the present results [25], the importance of mesoporous structure, physical and chemical properties have a great influence on the electrical properties of activated carbon. These characteristics influence conductivity by creating interconnected pathways within the carbon matrix, which facilitate electron flow and optimize conductivity levels for potential energy storage and electronic applications.

The field of application of resulting activated carbon derived from quail eggshells with a well-designed porous structure and tailored electrical properties can serve as a potential electrode material, contributing to improved energy storage and electron transfer capabilities. The expected practical impact of these functional groups lies in their ability to bind specific pollutants in adsorption applications or facilitate electron transfer in energy storage devices. For example, the presence of C=C bonds contributes to electrical conductivity, making the material suitable for advanced energy applications. Meanwhile, CaO groups can provide additional catalytic properties for chemical processes. The high microporosity enhances adsorption efficiency for removing heavy metals in wastewater treatment, while mesoporosity is essential for applications like energy storage, including supercapacitors and batteries.

Some limitations that should be taken into account include that this study only focuses on the effect of carbonization temperature on the porous structure and electrical conductivity of activated carbon derived from quail eggshells. The results are limited to these characteristics and do not extend to practical applications in adsorption or energy storage. Future research should aim to explore these applications by utilizing the optimized carbonization temperatures to assess their impact on real-world efficiency in these areas, enhancing both adsorption capacities and energy storage performance.

7. Conclusions

1. FTIR characterization of activated carbon from quail eggshells reveals functional groups including O-H, C-O, C-H, C=O, CaO, C=C, and CO_3^{2-}, with no changes in the types of functional groups observed across varying carbonization temperatures. However, changes were noted in transmittance values, indicating shifts in absorbance intensity.

2. XRD analysis shows a hexagonal crystal structure in all activated carbon samples. Increasing carbonization temperatures led to larger crystallite sizes (52.65 nm at 400 °C, 55.88 nm at 500 °C, and 58.67 nm at 600 °C) and higher crystallinity (54.38 %, 58.90 %, and 58.99 % for 400 °C, 500 °C, and 600 °C, respectively), confirming that higher temperatures enhance both crystal size and crystallinity.

3. SEM characterization indicates that at 400 °C and 500 °C, impurities and heterogeneous particle distributions were observed, while at 600 °C, activated carbon particles were more homogeneous, with clearer pore distribution. Particle sizes decreased as carbonization temperature increased, ranging from 0.71–10.16 μm at 400 °C to 0.73–7.57 μm at 600 °C, suggesting that higher temperatures produce finer, more uniform particles.

4. The largest surface area achieved was 296.875 m^2/g at a carbonization temperature of 400 °C. Surface area decreases with increasing carbonization temperature, likely due to pore blockage caused by ash aggregation, which limits available surface area at elevated temperatures.

5. The electrical conductivity of the quail eggshells-derived activated carbon reaches its highest value at $(1.62\times10^{-2}\pm2.43\times10^{-4})$ S/cm at a carbonization temperature of 400 °C. This high conductivity is associated with increased porosity, which facilitates better electron transfer across the material.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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