MJFAS
Malaysian Journal of Fundamental and Applied Sciences

Muhammad *et al.* | Malaysian Journal of Fundamental and Applied Sciences, Vol. 22 (2026) 763-775

RESEARCH ARTICLE

Effect of Carbonization Method on Local Poultry Waste-Derived Carbon as Potential Carbon Capture Adsorbent

[a,c]Muhammad Alif Muhaimin Mahasan,[a,b*]Mohd Hafiz Dzarfan Othman,[a,d]Mohd Zamri Mohd Yusop, [c]Nik Ahmad Nizam Nik Malek, [a,e]Mohd Hafiz Puteh, [a]Khong Nee Koo [a,f]Yusuf Olabode Raji, [g]Naoko Yoshida

[a]Advanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia; [b]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia; [c]Faculty of Science, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia; [d]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia; [e]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia; [f]Department of Chemical Engineering, Abubakar Tafawa Balewa University, Bauchi ATBU, Bauchi, Nigeria; [g]Institute of Materials and Systems for Sustainability, Nagoya University, Furocho, Chikusa-ku, Nagoya, Aichi, 464-8601, Japan

Abstract The valorisation of poultry waste into functional carbonaceous materials represents a sustainable strategy to address both waste management and environmental challenges associated with greenhouse gas emissions. In this study, chicken feathers, a keratin-rich biowaste, were utilized as a precursor for the synthesis of high-performance carbon material through urea-assisted pyrolysis using a double crucible method. Urea generates a semi-inert gaseous environment that promotes controlled thermal decomposition of the precursor during the modified carbonization process. Carbonization was carried out at three different temperatures: 650°C, 750°C, and 850°C with the same ramp rate (9°C/min) and dwell time (2 hours) to investigate the effect of urea on physicochemical properties such as the Brunauer–Emmett–Teller (BET) surface area and CO_2 adsorption capacity of the resulting carbon materials. The synthesized carbon material was characterized using Carbon Hydrogen Nitrogen Sulphur (CHNS) elemental analysis to quantify the carbon content and presence of nitrogen after the usage of urea in the sample and scanning electron microscopy (SEM) to elucidate morphological transformations and pore development. The results indicated that the modified method via urea significantly influenced the surface structure and porosity, with higher pyrolysis temperatures promoting more developed microporosity and larger specific surface areas, while also modifying the distribution of mesopores. At elevated temperatures, the enhanced decomposition of urea and volatilization of unstable species facilitated pore formation and structural rearrangement, leading to more accessible adsorption sites and improved textural properties. The carbon material carbonized at 850°C for 2 h with a ramp rate of 9°C/min exhibited a CO_2 adsorption capacity of 2.8 mmol g^{-1} at 1 bar and 273.15 K, which is comparable to that of the commercial activated carbon 3.64 mmol g^{-1} under the same conditions. This result suggests that the urea-modified carbon approaches the performance of commercial activated carbon, showing a significant CO_2 uptake despite being derived from waste-based precursors. These findings suggest that poultry feather-derived activated carbon represents a promising low-cost and sustainable adsorbent for biogas upgrading applications, contributing to cleaner energy production and advancing circular economy practices in the Malaysian context.

Keywords: Chicken feather; Carbon material, Urea-assisted carbonization, CO_2 capture; Adsorption.

***For correspondence:**
dzarfan@utm.my
Received: 06 Apr. 2026
Accepted: 10 Aug 2026

Introduction

The global demand for sustainable waste management and cleaner energy technologies has prompted the exploration of renewable materials with functional value. Biomass, particularly agricultural and poultry waste, offers potential as a feedstock for various environmental and energy-related applications [1]. Chicken feathers, a major byproduct of the poultry industry, are generated in large quantities worldwide, with an estimated 8.5 million tons produced annually as waste [2, 3, 4, 5]. In Malaysia, an estimated 17.745 million tons of waste is generated by chicken poultry. This amount is projected to increase, as Malaysians have the highest per capita chicken meat consumption in the world, with figures reaching 50.5kg per person in 2020 [6]. Traditionally, chicken feathers have been used as a protein-rich substrate for biogas production due to their high keratin and nitrogen content [7]. However, current disposal methods such as incineration or landfilling raise environmental concerns and fail to fully utilize the chemical potential of this waste. Alternative approaches that convert chicken feathers into high-value materials can contribute to both waste reduction and the development of sustainable products.

One promising direction is the transformation of chicken feathers into carbon-based filler. This valorisation approach has received increasing attention in recent years. Chicken feathers contain a significant amount of carbon-rich keratin, with reported carbon content ranging from 50% to 70% [8,9]. Their fibrous structure and surface chemistry make them suitable for conversion into porous carbon materials. Studies have shown that chicken feather-derived carbon has potential applications in water purification, energy storage, and catalysis. For instance, chicken feather-based activated carbon has been used for dye and heavy metal adsorption in wastewater [10], as electrode material for supercapacitors [11], and even in battery development [12]. These studies demonstrate that poultry waste can serve as a low-cost, renewable precursor for functional carbon materials.

Despite these promising results, the use of the principles of green chemistry by minimizing the use of chemicals and energy while maximizing resource efficiency for carbon capture applications remains limited. This sustainable material shows potential for CO_2 adsorption under general conditions, but further optimization is needed for broader industrial deployment especially to be on par with the traditional adsorbent materials such as activated carbon, zeolites, and metal-organic frameworks that have been widely used for this purpose [13]. Besides that, traditional adsorbents such as activated carbon, zeolites, and metal-organic frameworks have been widely investigated for carbon capture applications. However, these materials often involve costly synthesis processes and are not always derived from sustainable sources [14,15] thus their practical application is constrained by multiple challenges beyond economic considerations, including inherent low selectivity toward CO_2, complex and energy-intensive regeneration requirements, gradual deactivation over adsorption-desorption cycles due to thermal and chemical degradation, sensitivity to moisture and impurities, scalability difficulties in transitioning from laboratory to industrial scale, and operational constraints related to temperature and pressure conditions. Collectively, these limitations significantly impact the overall techno-economic viability and long-term sustainability of adsorption-based carbon capture systems. Therefore, there is a growing need to explore low-cost, renewable alternatives that are both efficient and environmentally friendly.

The approach adopted in this research supports the principles of green chemistry by utilizing a local biomass waste source. This method also aligns with circular economy strategies aimed at revalorizing waste streams [16]. Conventional activated carbons for CO_2 capture are typically produced from coal or imported biomass precursors and rely on chemical activation and external inert gas supplies, which increase cost, energy demand, and environmental footprint. These routes also underutilize locally available poultry residues such as chicken feathers, whose potential as a sustainable carbon precursor for CO_2 adsorbents remains weakly explored, especially under green, low-chemical carbonization schemes. The primary objective is to develop a sustainable carbon-based material for a potential carbon dioxide capture by using a urea-assisted double crucible carbonization method that generates a semi-inert atmosphere without external nitrogen gas and enables in situ nitrogen doping, aiming contributing to various applications, including biogas upgrading, direct air capture, industrial flue gas treatment, and post-combustion processes in power plants, thereby contributing to cleaner energy production and enhanced environmental sustainability

To achieve this objective, chicken feathers underwent urea-assisted carbonization in a double crucible configuration, where urea decomposition created a semi-inert atmosphere that eliminated the need for external inert gases while enabling in situ nitrogen doping. Carbonization temperatures of 650°C, 750°C, and 850°C were systematically varied to investigate their effects on pore development, nitrogen retention, and CO_2 adsorption performance. Key properties evaluated included Brunner–Emmett–Teller (BET) specific surface area, carbon-hydrogen-nitrogen-sulfur (CHNS) elemental composition,

morphological characteristics via scanning electron microscopy (SEM), and CO_2 uptake capacity, establishing correlations between synthesis conditions, textural properties, and gas capture efficiency.

Materials and Methods

Chicken feather poultry waste and high-purity urea were used in this study. The chicken feather poultry waste was obtained from a local chicken food processing business located in Skudai, Johor, Malaysia. High-purity urea (≥99%) was purchased from Sigma-Aldrich (USA) for use in the carbonization process. Commercial activated charcoal (DARCO, ~100 mesh particle size, powder, CAS No. 7440-44-0, Product No. 242276; Sigma-Aldrich, USA) was used to evaluate the textural properties and CO_2 adsorption performance of the chicken-feather-derived carbon samples [17]. The commercial activated charcoal was used as received without further treatment or modification. Its BET surface area, pore characteristics, and CO_2 adsorption capacity were evaluated under the same experimental conditions as the prepared carbon samples to ensure a consistent comparison.

Chicken feather purification process

Raw materials were collected and cleaned three times with water and detergent powder to remove external impurities such as dirt, mud, and blood. They were then rinsed multiple times until there were no obvious contaminants from the feathers. Afterward, the feathers were oven-dried for 24 hours at 80 °C or until fully dried. To ensure only the feather fibers were used, the rachis of the feathers was removed from the vane fibers carefully [3]. The feathers were ground using a grinder and the resulting powder was then put into the labelled container for further use.

Carbonization process of chicken feather

The samples then were carbonized at temperatures of 650 °C, 750 °C, and 850 °C using a laboratory-scale furnace (Carbolite Gero, HTF, U.K.) for a fixed holding time of 2 hours, with a constant heating ramp rate of 9°C/min. These temperatures and parameters were chosen to represent the progressive transformation from incomplete carbonization to a well-developed porous carbon network, as temperature critically governs pore evolution, nitrogen retention, and carbon yield.

A modified alternative approach known as the urea-assisted pyrolysis double crucible method was employed to simulate an inert atmosphere without the use of external gases, suitable for small-scale laboratory conditions [18]. In this method, the inner crucible containing the chicken feather precursor was placed inside an outer crucible partially filled with urea and insulated with ceramic wool, as shown in Figures 1(a) and 1(b). During heating, the thermal decomposition of urea generated gases, primarily NH_3 and CO_2, which scavenged the residual oxygen within the system and created a locally inert atmosphere. This approach removed the need for an external inert gas supply, such as nitrogen, providing a simpler, more cost-effective, and environmentally friendly method for achieving controlled pyrolysis. The outer crucible was covered with a loosely fitted lid to allow pressure release while minimizing air intrusion.

Following carbonization, the samples were thoroughly washed with ultrapure Milli-Q water (Millipore, USA) to remove any residual alkali, unreacted urea, and its decomposition products. The samples were gently stirred at 100 rpm for 15 min and subsequently vacuum-filtered. The washing and filtration steps were repeated until the filtrate reached a neutral pH [19]. The resulting carbon material was then oven-dried and ball-milled for 24 hours at 210 rpm until they became fined then sieved through a 36 µm mesh to eliminate any macroparticles. The final powder was stored in either a sealed glass bottle or a plastic clamp container for subsequent characterization and application experiments.

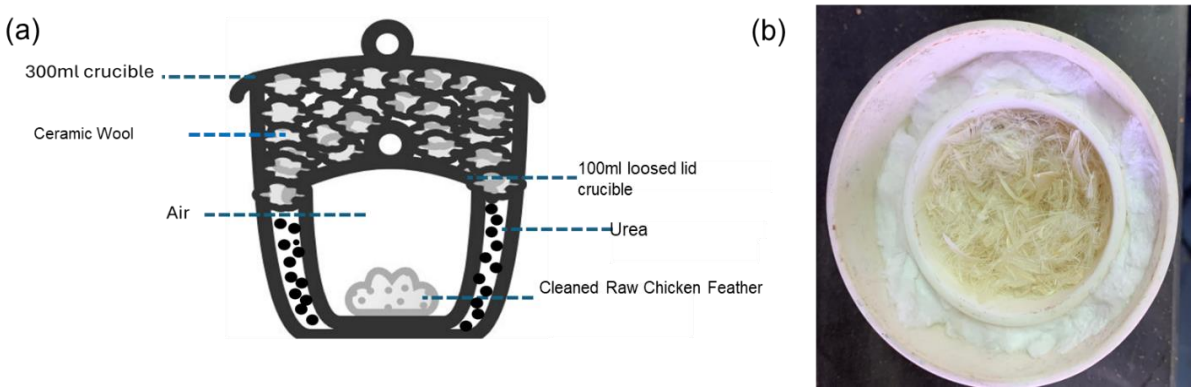


Figure 1.*(a)Schematic illustration of the modified double-crucible configuration used for nitrogen-assisted pyrolysis of chicken feathers, showing the arrangement of the outer crucible, ceramic wool insulation, urea as the nitrogen source, and the inner crucible containing cleaned raw chicken feathers; (b) photographic image showing the internal arrangement of the double-crucible setup prior to thermal treatment.*

Physicochemical characterization

The physicochemical characterization of the synthesized carbon materials was conducted to evaluate their structural and performance-related properties after carbonization

Percentage Yield

The yield of the carbon material was calculated to determine the effectiveness of produced carbon material after being carbonized. The samples were weight before the carbonization process and after the carbonization process. The percentage yield was calculated by the following formula

$$\text{Yield}\ (\%) = \left(\frac{\text{Mass of carbonized material}}{\text{Dry mass of raw precursor before pyrolysis}}\right) 100 \qquad [1]$$

Elemental Analysis

Carbon material underwent elemental analysis (CHNS) using an Elemental Analyzer (EAVM) to determine the percentage content of carbon and nitrogen in the chicken feathers after the carbonization process, which employed urea as a semi-assisted pyrolysis agent

Morphology

The Hitachi SU 8020 microscope was used for scanning electron microscopy (SEM) images. SEM was used to examine the surface morphology of the carbonized samples, allowing the visual identification of pores and estimation of their size range using an electron beam with acceleration voltages of up to 30 kV is focused on the specimen. Although not a precise pore size measurement method, SEM provides qualitative insight into pore development, complementing the quantitative data from BET analysis. SEM is a powerful and useful technique designed for examining the surface morphology of materials [20].

Surface Area

The Brunauer-Emmett-Teller (BET) specific surface area analysis was used to determine the pore size, surface area and micropore surface area of the carbon material produced using a Tristar II 3020 Micromeritics instrument. BET analysis was performed based on the adsorption isotherm of nitrogen gas at 77 K over a pressure range covering monolayer adsorption. Table 1 shows the parameters used for the analysis.

Table 1: Parameter of the BET Analysis used to determine the surface area of the sample

Parameter	Value
Analysis adsorptive	N_2
Analysis bath temp	273.150 K
Thermal Correction	No
Ambient Free Space	14.4513 cm^3
Port volume	-0.7618 cm^3
Low Pressure Dose	None
Automatic Degas	No

CO_2 Adsorption Capacity Measurements

Single-purged gas adsorption capacity isotherms were determined for CO_2 using a Tristar II 3020 Micromeritics instrument. The adsorption isotherms were obtained after sample regeneration under vacuum at a temperature of 273.15 degrees Kelvin for a duration of twelve hours. Carbon powders were degassed at 333.15 K to remove the moisture and other contaminants from their surface using FlowPrep 060 (Micromeritics). The data obtained from this method will indicate the volume of CO_2 adsorbed per gram in unit $\mathrm{mmol\ g^{-1}}$.

Results and Discussion

The results and discussion presented in this study systematically evaluate the influence of carbonization temperature under a urea-assisted double crucible configuration on the physicochemical properties and CO_2 adsorption performance of chicken feather-derived carbon materials. The analysis focuses on key parameters, including carbon yield, elemental composition, morphological evolution, textural properties, and adsorption capacity, in order to establish clear correlations between synthesis conditions and material functionality. These findings provide a comprehensive understanding of how controlled thermal treatment and in situ nitrogen incorporation contribute to the development of porous carbon structures suitable for gas separation applications. Detailed interpretations of each characterization and performance metric are provided in the subsequent subsections.

Percentage Yield

The carbon yield obtained from chicken feathers at different carbonization temperatures is summarized in Figure 2. From the data, it is clear that the carbon yield gradually decreases as the temperature increases, even though the heating rate (8 °C/min) and holding time (2 hours) were kept constant across all runs. The relatively high heating rate of 9 °C/min accelerates volatile release and limits the time available for secondary char-forming reactions, thereby reducing the overall carbon yield. This trend is supported by recent reviews reporting that increasing heating rates diminish char formation in biomass pyrolysis [21]. At 650 °C, the carbon yield was the highest, recorded at 27.17%. As the temperature increased to 750 °C, the yield dropped to 21.57%, and further decreased to 14.95% at 850 °C. This trend is expected and has been widely reported in biomass carbonization studies. As the temperature increases, more volatile components such as moisture, organics, and light gases were released from biomass [22,23]. This results in a smaller amount of solid residue left behind. In other words, higher temperatures promote deeper thermal degradation and decomposition, which in turn reduces the overall solid yield. However, despite this decline, the yields obtained in this study remain fairly substantial, particularly at 650 °C. The relatively high yield observed at lower temperatures may be attributed in part to the carbonization method used. In this study, a urea-assisted double-crucible method was applied, which mimics a semi-inert atmosphere similar to that typically achieved using nitrogen or argon in conventional setups. When comparing these results to those in the literature, the carbon yields achieved in this study are considered significant. For instance, a study by Onakwai et al. (2022) reported carbon yields of around 12–15% for chicken feathers carbonized between 400–600 °C without using any purging gas [24].

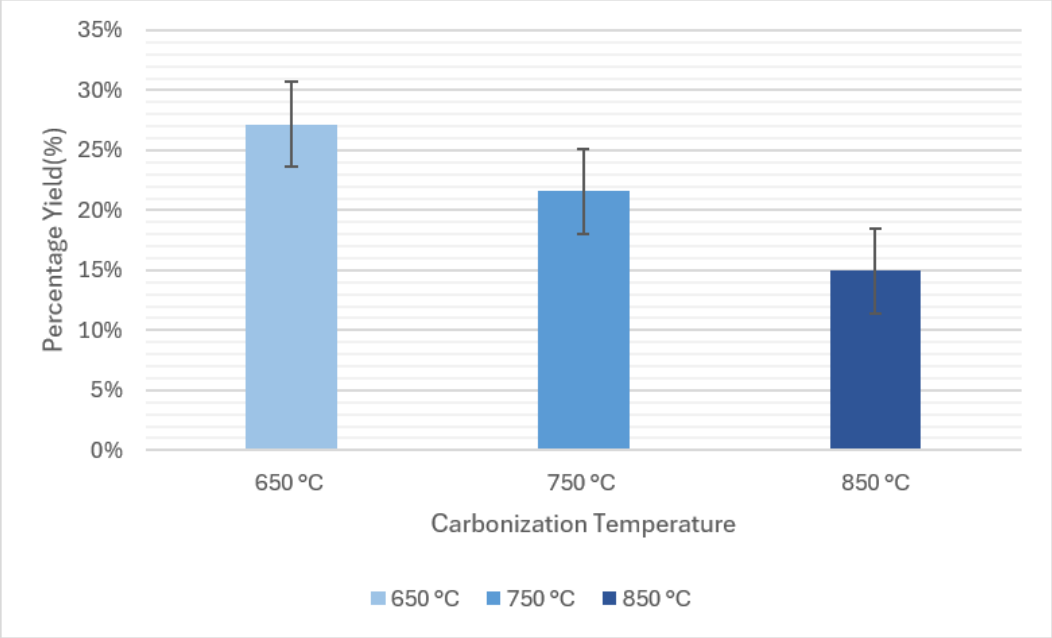
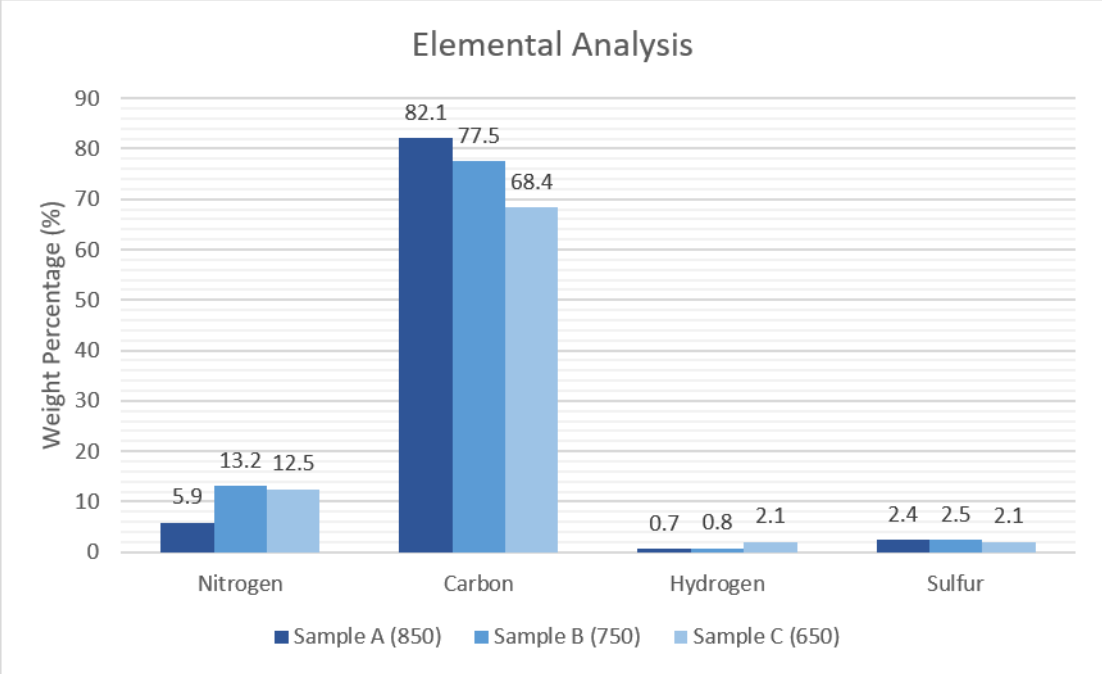


Figure 2. Percentage yield of chicken-feather-derived carbon prepared at different carbonization temperatures. Error bars represent mean ± standard deviation (n = 3).

Elemental analysis

The CHNS elemental analysis (Figure 3) reveals significant changes in elemental composition after carbonizing chicken feathers, especially in terms of carbon enrichment. At 850 °C, the carbon content reaches 82.10%, compared to the typical 45–70% in raw chicken feathers [4,9]. This shows that carbonization under the modified setup can effectively remove non-carbon elements and concentrate the carbon structure. The trend is consistent across temperatures, where carbon increases from 68.4% at 650 °C to 77.5% at 750 °C, and then to 82.1% at 850 °C. In contrast, nitrogen, hydrogen, and sulphur contents decrease with higher temperature, which is expected due to the release of volatile compounds and the condensation of the carbon framework.

Although urea was not specifically added to introduce nitrogen into the carbon structure, its decomposition during pyrolysis likely released gases such as ammonia (NH_3) and isocyanic acid (HNCO), which may have unintentionally allowed some nitrogen to be incorporated into the carbon material [17]. The CHNS results show that nitrogen is still present, particularly at the lower pyrolysis temperature, suggesting that a small amount of nitrogen doping may have occurred.



.

Figure 3. Elemental composition of carbon, hydrogen, nitrogen, and sulphur determined by CHNS analysis.

Effect of temperature on morphology

SEM micrographs obtained at 2.0kx magnification (Figure 4) revealed clear morphological variations in the carbon materials as a function of carbonization temperature. At 650 °C, the surface appeared relatively compact with fewer visible pores, while the sample carbonized at 750 °C exhibited a more heterogeneous texture with the emergence of irregular voids. In contrast, the 850 °C sample displayed the most pronounced porous features, indicating that elevated temperatures promote enhanced structural development. These observations suggest that higher thermal treatment favors the evolution of pore networks, which is consistent with the improved textural properties typically reported for carbons produced at elevated temperatures. It should be noted, however, that SEM provides only qualitative insights into morphology at the micron scale and does not resolve micropores or deliver quantitative surface area data. Hence, the SEM results are better interpreted as indicators of morphological trends, with detailed pore structure and surface area characterization requiring complementary analyses such as BET.

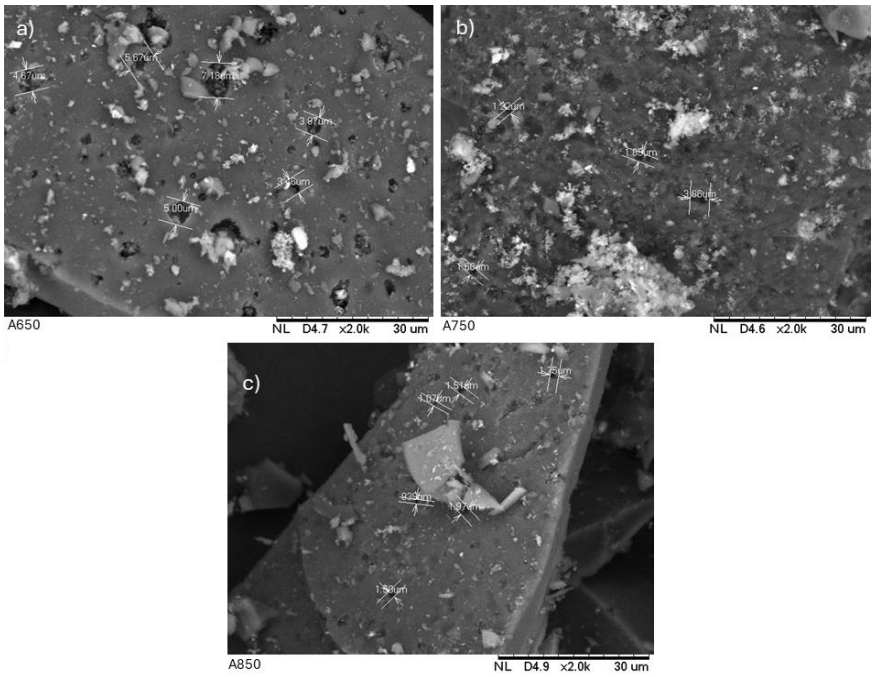


Figure 4. Effect of the temperature on the morphology at (a) 650 °C (b) 750 °C, and (c) 850 °C

Surface area and pore size

The effect of carbonization temperature on the textural properties of the synthesized carbon materials is evident from the BET surface area, pore size, and microporosity results (Table 1). Increasing the carbonization temperature from 650 to 850 °C progressively improved the surface area and microporous structure. At 650 °C, the carbon exhibited a BET surface area of 330.83 m^2/g, an average pore size of 2.11 nm, a micropore area of 211.15 m^2/g, and a micropore volume of 0.09 cm^3/g, indicating the initial development of a porous carbon structure. Increasing the temperature to 750 °C significantly enhanced the BET surface area to 467.56 m^2/g, while reducing the average pore size to 1.86 nm. The micropore area and volume also increased to 407.03 m^2/g and 0.16 cm^3/g, respectively, suggesting more extensive pore formation. At 850 °C, the BET surface area reached its highest value of 496.09 m^2/g, accompanied by a slight increase in pore size to 1.95 nm, while the micropore area and volume increased marginally to 421.85 m^2/g and 0.17 cm^3/g, respectively. Compared with the commercial activated carbon, which exhibited a BET surface area of 830.53 m^2/g and a micropore area of 550.05 m^2/g, the synthesized carbon produced at 850 °C showed lower textural properties but demonstrated considerable micropore development without any chemical activation. Overall, increasing the carbonization temperature promoted the formation of a more microporous carbon structure with a larger surface area, making it more suitable for adsorption applications.

Table 1. BET surface area, t-plot micropore area, and t-plot micropore volume at different carbonization temperatures

Sample	BET surface area (m^2g)	Pore Size (nm)	t-Plot Micropore Area, m^2/g	t-plot Micropore volume, cm^3/g
Commercial AC	830.53	2.72	550.05	0.23
650	330.83	2.11	211.15	0.09
750	467.56	1.86	407.03	0.16
850	496.09	1.95	421.85	0.17

CO_2 Adsorption Capacity

The CO_2 adsorption capacities of the carbon materials prepared at different carbonization temperatures clearly demonstrate the influence of the carbonization process on adsorption performance. As illustrated in Figure 5, the commercial activated carbon exhibited the highest CO_2 adsorption capacity of 3.64 mmol g^{-1} and was used as a benchmark for comparison with the developed carbon materials. Among the prepared samples, the carbon material produced at 650 °C showed the lowest CO_2 adsorption capacity of 1.45 mmol g^{-1}. This relatively limited uptake is attributed to the less developed microporous structure at this carbonization temperature, which provides fewer accessible adsorption sites for CO_2 molecules.

Increasing the carbonization temperature to 750 °C significantly enhanced the CO_2 adsorption capacity to 2.65 mmol g^{-1}, representing an increase of approximately 82.8% compared with the sample prepared at 650 °C. This improvement is consistent with the BET analysis, which revealed a substantial increase in both the specific surface area and micropore area. A further increase in carbonization temperature to 850 °C resulted in the highest CO_2 adsorption capacity among the prepared carbon materials, reaching 2.80 mmol g^{-1}. The enhanced adsorption performance is primarily attributed to the continued development of the microporous structure and the increase in BET surface area. Although CHNS analysis indicated that the nitrogen content decreased with increasing carbonization temperature, the improved pore structure exerted a greater influence on CO_2 adsorption than the nitrogen content under the investigated conditions. These results suggest that well-developed microporosity is the dominant factor governing CO_2 adsorption performance.

A comparison with recent literature further demonstrates the competitiveness of the prepared carbon material. As summarized in Table 3, Zhang et al. (2022) reported an activation-free nitrogen-doped biochar with a CO_2 adsorption capacity of 2.43 mmol g^{-1} despite the absence of conventional chemical activation [25]. Although the adsorption measurements were performed at 303 K, which generally results in lower CO_2 uptake than measurements conducted at 273.15 K, the comparable adsorption performance highlights the effectiveness of nitrogen-assisted carbonization for developing adsorption-active porous structures. Unlike many reported biomass-derived carbon adsorbents that rely on KOH, $ZnCl_2$, or H_3PO_4 activation to enhance porosity [26, 27, 28], the present study employed only a urea-assisted double-crucible carbonization process without conventional chemical activation. This demonstrates that competitive CO_2 adsorption can be achieved through a relatively simple and environmentally friendly synthesis route.

Although the commercial activated carbon outperformed the prepared samples, the carbon material produced at 850 °C achieved approximately 76.9% of the commercial adsorption capacity without the use of conventional chemical activating agents or a continuous external inert gas supply during carbonization. Considering that the adsorbent was synthesized from an abundant poultry waste resource using a simple and sustainable carbonization approach, this level of performance is highly encouraging. These findings highlight the potential of the urea-assisted double-crucible carbonization method as an environmentally friendly strategy for producing nitrogen-doped carbon adsorbents suitable for CO_2 capture and biogas upgrading applications.

Table 2. Comparison of the BET surface area and CO_2 adsorption capacity of the prepared carbon materials with representative biomass-derived carbon adsorbents reported in the literature.

Sample	Preparation method	BET surface area (m^2 g^{-1})	CO_2 adsorption (mmol g^{-1})	Adsorption conditions	Reference
Modified 650	Urea-assisted double-crucible carbonization	330.83	1.45	273.15 K, 1 bar	This work
Modified 750	Urea-assisted double-crucible carbonization	467.56	2.65	273.15 K, 1 bar	This work
Modified 850	Urea-assisted double-crucible carbonization	496.09	2.80	273.15 K, 1 bar	This work
Activation-free N-doped biochar	Nitrogen doping via ZIF-8-assisted carbonization	989.30	2.43	303 K, 1 bar	Zhang et al. (2022) [25]
Commercial AC	Not stated	830.53	3.64	273.15 K, 1 bar	This work

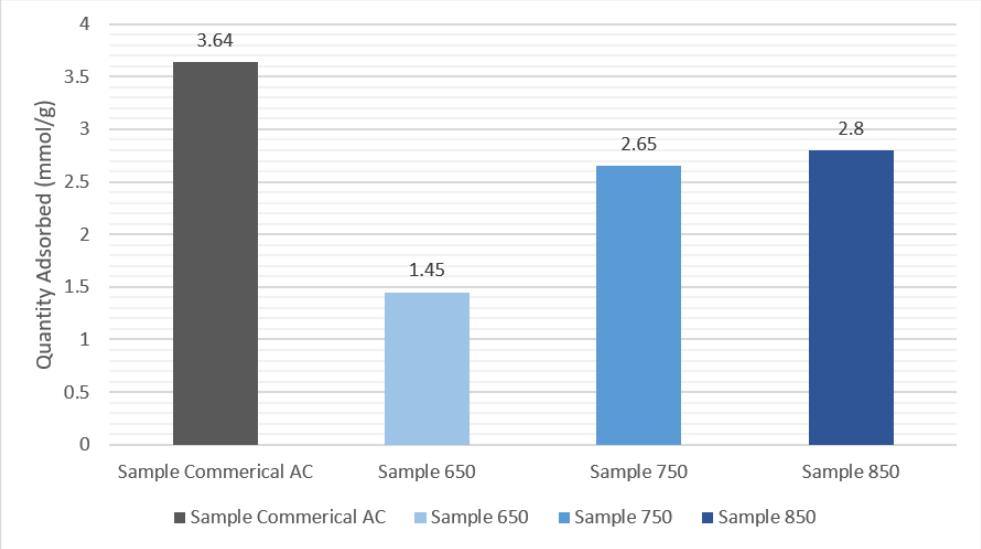


Figure 5. Comparison of CO_2 adsorption capacity of commercial activated carbon (AC) and chicken feather waste-derived carbon materials carbonized at different temperatures (650–850 °C) at 273.15 K and 1 bar.

CO_2 Adsorption–Desorption Isotherm

Figure 6 presents the CO_2 adsorption–desorption isotherms of the prepared carbon materials together with the commercial activated carbon at 273.15 K using both linear and logarithmic relative-pressure scales. As shown in Figure 6(a), CO_2 uptake increased steadily with increasing relative pressure for all samples, although the extent of adsorption varied with carbonization temperature. Among the prepared carbon materials, the sample carbonized at 850 °C consistently exhibited the highest CO_2 adsorption capacity, followed by the 750 °C and 650 °C samples. This trend is consistent with the BET results, which showed that increasing the carbonization temperature promoted the development of the microporous structure and increased the available surface area for CO_2 adsorption.

The adsorption and desorption branches of the prepared carbon materials remained relatively close throughout the investigated pressure range, suggesting that a substantial proportion of the adsorbed CO_2 could be released during desorption. This behaviour indicates that the adsorption process is largely reversible and suggests that the prepared carbon materials may possess regeneration potential under the applied experimental conditions. However, confirmation of regeneration performance requires repeated adsorption–desorption cycling. A small hysteresis loop was observed, particularly at higher relative pressures, which may be associated with restricted diffusion within narrow micropores or slight differences in pore accessibility during the adsorption and desorption processes [29]. Such behaviour is commonly reported for microporous carbon materials, where CO_2 adsorption is predominantly governed by micropore filling [30,31].

The logarithmic isotherms shown in Figure 6(b) provide a more detailed view of the adsorption behaviour at low relative pressures, where differences between the samples become more distinguishable. All prepared carbon materials exhibited a rapid increase in CO_2 uptake in this region, indicating favourable interactions between CO_2 molecules and the accessible microporous structure. The sample carbonized at 850 °C maintained the highest adsorption capacity across the entire pressure range, further supporting the role of well-developed microporosity in enhancing adsorption performance. These observations are in good agreement with the BET and CHNS analyses, which together suggest that the progressive development of the pore structure with increasing carbonization temperature played a more dominant role in improving CO_2 adsorption than nitrogen content under the present experimental conditions.

Although the adsorption–desorption isotherms provide useful preliminary insight into the regeneration potential of the prepared carbon materials, they represent only a single adsorption–desorption measurement for each sample. Consequently, the present results should be interpreted as an indication of adsorption reversibility rather than definitive evidence of long-term reusability or cyclic stability.

.

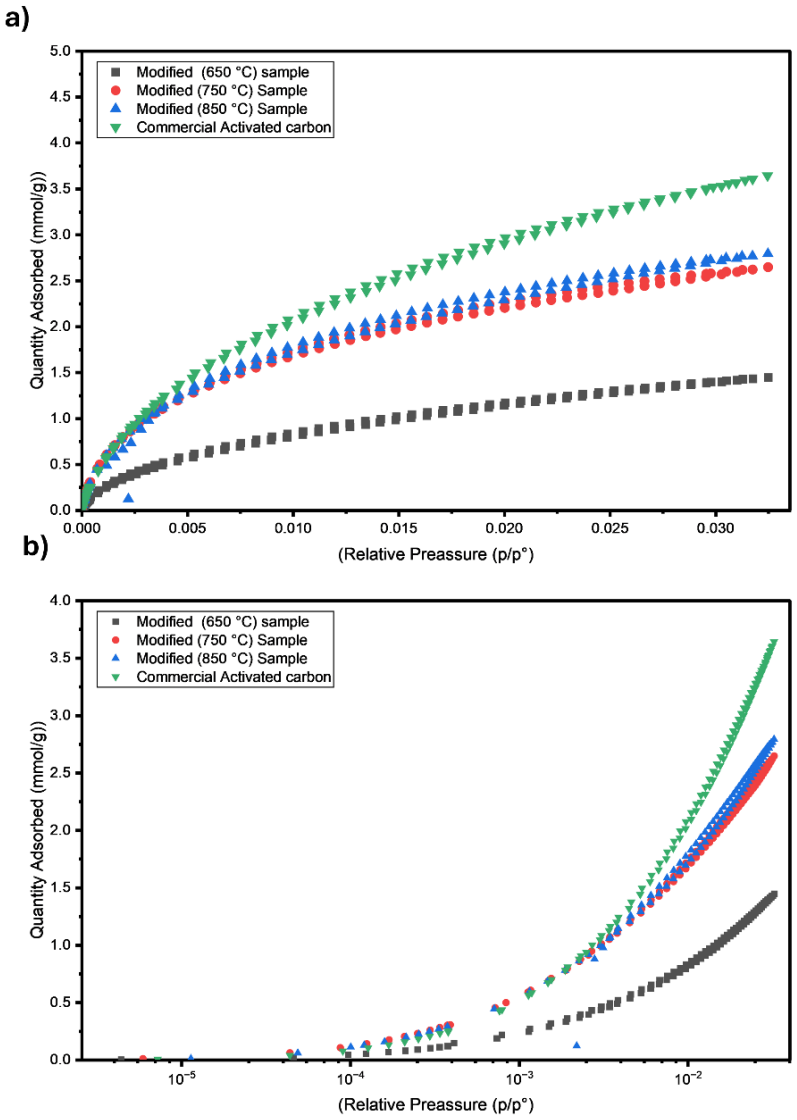


Figure 6. CO_2 adsorption–desorption isotherms of carbon materials prepared at 650, 750, and 850 °C at 273.15 K: (a) linear relative-pressure scale and (b) logarithmic relative-pressure scale.

Conclusions and future work

In conclusion, chicken feather-derived carbon materials produced through urea-assisted double-crucible carbonization showed promising potential for CO_2 adsorption. Among the samples investigated, the material carbonized at 850 °C achieved the highest CO_2 adsorption capacity of 2.8 mmol g^{-1} at 1 bar and 273.15 K, equivalent to approximately 76.92% of the capacity achieved by commercial activated carbon (3.64 mmol g^{-1}). Notably, this performance was obtained without the use of an external inert gas supply or conventional chemical activating agents. The prepared materials exhibited BET surface areas ranging from approximately 330.83 to 496.09 m^2/g, while CHNS analysis revealed a gradual decrease in nitrogen content from 12.5 wt% at 650 °C to 5.9 wt% at 850 °C as the carbonization temperature increased. Taken together, these findings demonstrate the potential of chicken feather-derived carbon as a sustainable adsorbent for CO_2 capture and related applications, particularly biogas upgrading. The urea-assisted double-crucible configuration also provides a semi-inert environment during carbonization without requiring a continuous supply of external inert gas. In addition, the double-crucible design improved the carbon yield by approximately 25–30% compared with direct carbonization, suggesting

that this approach could offer a more sustainable route for converting chicken feather waste from the Malaysian poultry industry into value-added carbon materials.

Further work is needed to gain a more complete understanding of the structural and surface properties of the developed materials. Characterization using X-ray diffraction (XRD), Raman spectroscopy, and Fourier-transform infrared (FTIR) spectroscopy on samples thoroughly washed with ultrapure water would help clarify the carbon structure, residual nitrogen incorporation, and surface functional groups. Complementary pH measurements could also provide useful information on the surface chemistry of the resulting materials. Further optimization of the urea-to-feather mass ratio is recommended to improve nitrogen retention, potentially maintaining the nitrogen content above 8 wt%, while establishing how these changes affect surface basicity and CO_2 adsorption performance. Systematic cyclic adsorption–desorption experiments over multiple consecutive cycles are also necessary to quantitatively assess regeneration efficiency, CO_2 adsorption capacity retention, and long-term cyclic stability. Such investigations would provide a clearer understanding of the material's reusability and its suitability for repeated CO_2 capture applications. Beyond laboratory-scale evaluation, a techno-economic feasibility assessment of continuous-flow production systems adapted to local poultry-processing facilities in Malaysia would be valuable in determining the industrial viability and scalability of this carbonization approach. Overall, this study supports the principles of a circular economy by exploring a practical route for transforming locally abundant chicken feather waste into value-added functional carbon materials. In doing so, it contributes to the sustainable utilization of poultry waste while offering a potential pathway towards greener materials for CO_2 capture and gas separation technologies.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

The authors gratefully acknowledge the financial support from the Ministry of Higher Education Malaysia for the funding through project grant of the Science and Technology Research Partner for Sustainable Development (SATREPS) (Project Number: SATREPS/UTM/PF/KPT23/ R.J130000.7809.4L975). The authors also would like to thank Universiti Teknologi Malaysia under Matching Grant with Sriwijaya University, Indonesia (Project Number: R.J130000.7301.1U055).

References

[1] Z. Usmani *et al.*, “Bioprocessing of waste biomass for sustainable product development and minimizing environmental impact,” Feb. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.biortech.2020.124548.

[2] A. A. Alhamidi, T. Partuti, and D. Rachmawati, “Production of Activated Carbon from Chicken Feathers As An Alternative Hydrogen Storage,” in *Journal of Physics: Conference Series*, Institute of Physics Publishing, Nov. 2019. doi: 10.1088/1742-6596/1376/1/012034.

[3] Z. Mohammed, S. Jeelani, N. S. Korivi, and V. Rangari, “Synthesis and characterization of N-doped porous carbon from chicken feathers for 3D printed electrode applications,” 2022, doi: 10.21203/rs.3.rs-2230929/v1.

[4] N. de A. Pedrosa, C. J. de Andrade, J. C. C. Petrus, and A. R. Monteiro, “Sequential hydrolysis of chicken feathers composed of ultrasound and enzymatic steps: an enhanced protein source with bioactive peptides,” *Biomass*, vol. 2, no. 4, pp. 237–249, 2022.

[5] M. D. Álvarez-del-Castillo, N. Garrido-Soriano, M. Casadesús, J. Macanás, G. Molins-Duran, and F. Carrillo-Navarrete, “Environmental Impact of Chicken Feathers Based Polypropylene Composites Developed for Automotive and Stationary Applications and Comparison with Glass-Fibre Analogues,” *Waste Biomass Valorization*, vol. 13, no. 11, pp. 4585–4598, Nov. 2022, doi: 10.1007/s12649-022-01810-0.

[6] N. F. Sabri, N. F. Omar, N. Z. Samsuddin, and M. A. H. Azhar, “Biodegradation of Chicken Feather Waste with Bacillus subtilis in Vermicomposting,” *Pertanika J. Trop. Agric. Sci.*, vol. 48, no. 4, pp. 1297–1312, 2025, doi: 10.47836/pjtas.48.4.13.

[7] M. Farhad Ali, M. Sahadat Hossain, T. Siddike Moin, S. Ahmed, and A. M. Sarwaruddin Chowdhury, “Utilization of waste chicken feather for the preparation of eco-friendly and sustainable composite,” *Clean. Eng. Technol.*, vol. 4, no. June, pp. 4–10, 2021, doi: 10.1016/j.clet.2021.100190.

[8] T. Tesfaye, B. Sithole, D. Ramjugernath, and V. Chunilall, “Valorisation of chicken feathers: Characterisation of chemical properties,” *Waste Management*, vol. 68, pp. 626–635, 2017, doi: https://doi.org/10.1016/j.wasman.2017.06.050.

[9] T. Tesfaye, B. Sithole, and D. Ramjugernath, “Valorisation of chicken feather barbs: Utilisation in yarn production and technical textile applications,” *Sustain. Chem. Pharm.*, vol. 8, pp. 38–49, Jun. 2018, doi: 10.1016/j.scp.2018.02.002.

[10] R. Chiramba, G. Charis, N. Fungura, G. Danha, and T. Mamvura, “Production of activated carbon from

poultry feathers for waste water treatment," *Water Science and Technology*, vol. 80, no. 8, pp. 1407–1412, 2019.

[11] Z. Zhao, Y. Wang, M. Li, and R. Yang, "High performance N-doped porous activated carbon based on chicken feather for supercapacitors and CO2 capture," *RSC Adv.*, vol. 5, no. 44, pp. 34803–34811, 2015, doi: 10.1039/c5ra01569c.

[12] E. Hastuti, A. Subhan, and D. Puspitasari, "Synthesis of activated carbon derived from chicken feather for Li-ion batteries through chemical and physical activation process," *Mater. Renew. Sustain. Energy*, vol. 10, no. 3, Sep. 2021, doi: 10.1007/s40243-021-00198-6.

[13] H. M. Mahmudul, D. Akbar, M. G. Rasul, R. Narayanan, and M. Mofijur, "Estimation of the sustainable production of gaseous biofuels, generation of electricity, and reduction of greenhouse gas emissions using food waste in anaerobic digesters," *Fuel*, vol. 310, p. 122346, 2022.

[14] B. Aghel, S. Behaein, S. Wongwises, and M. S. Shadloo, "A review of recent progress in biogas upgrading: With emphasis on carbon capture," *Biomass Bioenergy*, vol. 160, p. 106422, 2022.

[15] S. F. Ahmed *et al.*, "Biogas upgrading, economy and utilization: a review," *Environ. Chem. Lett.*, vol. 19, no. 6, pp. 4137–4164, 2021.

[16] F. J. Lozano *et al.*, "New perspectives for green and sustainable chemistry and engineering: Approaches from sustainable resource and energy use, management, and transformation," *J. Clean. Prod.*, vol. 172, pp. 227–232, 2018, doi: https://doi.org/10.1016/j.jclepro.2017.10.145.

[17] M. Fauziyah, W. Widiyastuti, and H. Setyawan, "Nitrogen-Doped Carbon Aerogels Prepared by Direct Pyrolysis of Cellulose Aerogels Derived from Coir Fibers Using an Ammonia–Urea System and Their Electrocatalytic Performance toward the Oxygen Reduction Reaction," *Ind. Eng. Chem. Res.*, vol. 59, no. 49, pp. 21371–21382, Dec. 2020, doi: 10.1021/acs.iecr.0c03771.

[18] M. D. Mehare, A. D. Deshmukh, and S. J. Dhoble, "Preparation of porous agro-waste-derived carbon from onion peel for supercapacitor application," *J. Mater. Sci.*, vol. 55, no. 10, pp. 4213–4224, 2020, doi: 10.1007/s10853-019-04236-7.

[19] M. Luo, J. Chen, Q. Li, and Y. Wang, "Cotton-Based Activated Carbon Fiber with High Specific Surface Area Prepared by Low-Temperature Hydrothermal Carbonization with Urea Enhancement," *Ind. Eng. Chem. Res.*, vol. 62, no. 22, pp. 8744–8753, Jun. 2023, doi: 10.1021/acs.iecr.3c00807.

[20] B. J. Inkson, "2 - Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for materials characterization," in *Materials Characterization Using Nondestructive Evaluation (NDE) Methods*, G. Hübschen, I. Altpeter, R. Tschuncky, and H.-G. Herrmann, Eds., Woodhead Publishing, 2016, pp. 17–43. doi: https://doi.org/10.1016/B978-0-08-100040-3.00002-X.

[21] W. Jerzak, E. Acha, and B. Li, "Comprehensive Review of Biomass Pyrolysis: Conventional and Advanced Technologies, Reactor Designs, Product Compositions and Yields, and Techno-Economic Analysis," *Energies (Basel).*, vol. 17, no. 20, 2024, doi: 10.3390/en17205082.

[22] R. Chiramba, G. Charis, N. Fungura, G. Danha, and T. Mamvura, "Production of activated carbon from poultry feathers for waste water treatment," *Water Science and Technology*, vol. 80, no. 8, pp. 1407–1412, Oct. 2019, doi: 10.2166/wst.2019.388.

[23] O. Üner and Y. Bayrak, "The effect of carbonization temperature, carbonization time and impregnation ratio on the properties of activated carbon produced from Arundo donax," *Microporous and mesoporous Materials*, vol. 268, pp. 225–234, 2018.

[24] A. O. Onokwai, E. S. A. Ajisegiri, I. P. Okokpujie, R. A. Ibikunle, M. Oki, and J. O. Dirisu, "Characterization of lignocellulose biomass based on proximate, ultimate, structural composition, and thermal analysis," *Mater. Today Proc.*, vol. 65, pp. 2156–2162, 2022, doi: https://doi.org/10.1016/j.matpr.2022.05.313.

[25] J. Zhang *et al.*, "Activation-free synthesis of nitrogen-doped biochar for enhanced adsorption of CO2," *J. Clean. Prod.*, vol. 355, p. 131642, 2022, doi: https://doi.org/10.1016/j.jclepro.2022.131642.

[26] H. Nam, W. Choi, D. A. Genuino, and S. C. Capareda, "Development of rice straw activated carbon and its utilizations," *J. Environ. Chem. Eng.*, vol. 6, no. 4, pp. 5221–5229, 2018.

[27] Z. Heidarinejad, M. H. Dehghani, M. Heidari, G. Javedan, I. Ali, and M. Sillanpää, "Methods for preparation and activation of activated carbon: a review," *Environ. Chem. Lett.*, vol. 18, pp. 393–415, 2020.

[28] G. Sethia and A. Sayari, "Activated carbon with optimum pore size distribution for hydrogen storage," *Carbon N. Y.*, vol. 99, pp. 289–294, 2016.

[29] T. Zelenka, L. Zelená, C. Abreu-Jaureguí, J. Silvestre-Albero, G. Zelenková, and V. Slovák, "On the Low-Pressure Hysteresis (LPH) in Gas Sorption Isotherms of Porous Carbons," *Small*, vol. 20, no. 36, p. 2311990, Sep. 2024, doi: https://doi.org/10.1002/smll.202311990.

[30] M. Karimi, M. Shirzad, J. A. C. Silva, and A. E. Rodrigues, "Carbon dioxide separation and capture by adsorption: a review," *Environ. Chem. Lett.*, vol. 21, no. 4, pp. 2041–2084, 2023, doi: 10.1007/s10311-023-01589-z.

[31] Y. Zhao, X. Liu, and Y. Han, "Microporous carbonaceous adsorbents for CO2 separation via selective adsorption," *RSC Adv.*, vol. 5, no. 38, pp. 30310–30330, Apr. 2015, doi: 10.1039/c5ra00569h.