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CHARACTERISATION OF EGG WHITE-IMPREGNATED ACTIVATED CARBON FOR CO_2 ADSORPTION APPLICATION

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Abstract: In this study egg white was used as a source of natural amino acids to modify the surface properties of palm shell-based activated carbon to enhance its CO_2 capture performance. A simple impregnation method was employed for this purpose. Characterisation analysis was performed on the egg white-impregnated activated carbon to examine any changes in its surface properties before the CO_2 adsorption test. The modified adsorbent showed high thermal stability below 300 °C and comprised of a new amide functional group. Furthermore, the modified adsorbent exhibited a 31% higher breakthrough time and maintained its CO_2 adsorption capacity at 0.3 mmol/g, in comparison to raw activated carbon, regardless of the surface area and micropore volume reductions of 17% and 18%, respectively. These findings provide evidence for the prospect of using egg white-impregnated activated carbon for CO_2 adsorption applications, which could lead to a new generation of affordable and eco-friendly adsorbents.

Keywords: Activated carbon, CO_2 capture, CO_2 adsorption, Natural Amino Acids, Egg White

1. Introduction

Carbon dioxide (CO_2) emissions account for about 76% of all global greenhouse gas emissions, leading to climate warming (U.S. EPA, 2023). In fact, the sudden drop in daily carbon dioxide (CO_2) emissions during the pandemic in 2019 due to measures like stringent movement control orders demonstrated that human activities are contributing to the rise of global CO_2 concentration (Le Quéré et al., 2020; Rasmussen, 2021). Although major efforts have been made worldwide to reduce CO_2 emissions, in the long run, more sustainable ways are still required from the social, environmental and economic perspectives. One key solution to this issue is to implement Carbon Capture and Sequestration (CCS) technology, preferably by post-combustion mode which can be easily integrated into existing plants (Allangawi et al., 2023). Of the post-combustion methods available, adsorption constitutes to a highly profitable and effective means of CO_2 capture, consuming less energy than the conventional absorption process (Khan et al., 2023).

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Typical groups of adsorbents include activated carbons, polymeric materials, zeolites, silica and metal–organic frameworks (MOFs). However, the efficiency of capturing CO_2 using solid sorbents (adsorbents) always depend on the selection of a suitable adsorbent for use in a particular application (Ketabchi et al., 2023). Subsequently, these adsorbents are generally subjected to physicochemical treatment to enhance their surface functionalities and thus increase their CO_2 selectivity. Malaysia has abundant biomass/biowaste resources that could be converted into activated carbon. These biomass-derived forms of carbon are inexpensive and can be further modified for improved surface functionalities (Nazir et al., 2023). However, the solvents commonly used as modifying agents during the treatment are alkaline metal salts, strong acids and amine-based solvents, which have proven less environmentally friendly (Shu Hui & Ahmad Zaini, 2015; You & Kim, 2020). Therefore, a sustainable approach would be to use green solvents like natural-based ionic liquids (ILs) and deep eutectic solvents (DESs) (Vanda et al., 2018; Zhao et al., 2021). These solvents not only possess low toxicity and high biodegradability but also potentially reduce material costs owing to the cheap, abundant and easily accessible natural compounds, i.e., organic acids and bases, amino acids, sugars and choline (Vanda et al., 2018). Of these, amino acid was found to be prominently functionalised with IL (AAIL) and DES (Suhaili et al., 2023), and it was used as a modifying agent with porous solids, suggesting its efficiency in facilitating the CO_2 capture process (Balsamo et al., 2018; Philip & Henni, 2023).

Pure single amino acids can be easily obtained commercially but they cost more than other natural compounds. Alternatively, amino acids can be sourced from foods and plants. For example, Imtiaz-Ul-Islam et al. (2011) determined that whey protein could

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adsorb CO_2 over 15 cycles with a minimal loss of capacity, a better result compared to activated carbon and zeolites. Other recent literature has explored the use of egg white in fabricating nitrogen-doped materials but in other applications such as wastewater treatment (Chen et al., 2022; Wang et al., 2020) and high-performance supercapacitor electrodes (Zhu et al., 2019). Furthermore, Gil-Lalaguna et al. (2022) reported that protein-containing livestock wastes can also be converted into pyrolysis char and used as a CO_2 adsorbent, although they exhibited a lower adsorption capacity than pure proteins. Albumen (egg whites) is closer to a pure amino acids chain than other sources of natural amino acids and could offer immense potential as a surface modifying agent. Some bakery and cosmeceutical industries discard large amounts of egg white, normally during pastry making and antibody cultivation (Lu et al., 2022). From this perspective, repurposing egg white waste might not only promote the circular economy but also help in addressing two environmental issues at once (waste management and climate warming).

This paper presents a preliminary investigation into the CO_2 adsorption performance and characteristics of palm shell-based activated carbon after impregnation with 50 wt.% of egg white solution. In comparison to raw activated carbon, the egg white-impregnated activated carbon was characterised using a field emission scanning electron microscope with energy-dispersive x-ray (FESEM-EDX), while a surface area and pore volume analyser was used to examine the changes in surface physical properties and elemental compositions. To determine the chemical properties, Fourier transform infrared (FTIR) spectroscopy was performed to analyse the functional groups of the adsorbent. The thermal stability of the adsorbent was also inspected using a simultaneous thermal analyser (STA) before the CO_2 adsorption test using a packed-bed column. Two fundamental parameters pertaining to CO_2 adsorption performance are the breakthrough time and CO_2 adsorption capacity, which were also measured.

2. Experiment

2.1 Materials

Fresh chicken eggs were purchased from a local supermarket, while palm kernel shell-based activated carbon (C2889, Sigma-Aldrich) was purchased from the supplier. The purified carbon dioxide (99.8%) and nitrogen (99.995%) gases were supplied by Alpha Gas Solution Sdn. Bhd., Malaysia.

Preparation of egg white impregnated activated carbon

The activated carbon (AC) was initially washed and oven-dried overnight at 100-120 °C to remove impurities and fine particles. The dried AC was then kept in a desiccator until needed. An egg white (EW) concentration of 50 wt.% was selected as an initial study. To prepare the solution, EW was separated from the yolk before being diluted with deionised (DI) water to produce a solution with a 1:1 ratio in terms of weight. The solution was then added to the dried AC and left for 24 hours at room temperature (25 °C) before being oven-dried at 50 °C to allow the EW solution to disperse into the pore surfaces of the AC (Mohamed Hatta et al., 2023).

2.2 Characterisation

The impregnated AC was characterised using a field emission scanning electron microscope with energy-dispersive x-ray spectroscopy (FESEM-EDX) (Tescan Analytics, TESCAN VEGA3, Czech Republic) for the surface morphology and elemental composition analyses. Fourier transform infrared (FTIR) spectroscopy (Bruker, VERTEX 70v, USA) was used to analyse the changes in chemical bonds and functional groups present after the modification process. A Micromeritics accelerated surface area and porosity (ASAP) 2020 instrument was used to determine the surface area and pore volume. To ascertain the thermal decomposition of the sample, a simultaneous thermal analysis (STA) was performed under 20 mL/min of nitrogen (N_2) flow at a heating rate of 10 °C/min.

2.3 CO_2 adsorption test

The CO_2 adsorption performance of the EW-impregnated AC was evaluated using a system with a single packed-bed column under atmospheric pressure (1 atm). The test was conducted at a temperature of 25 °C and a flow rate of 200 mL/min (15 vol.% CO_2/N_2). The adsorption column filled with the sample was purged with the N_2 flow to remove other gases from the column and those that were readily adsorbed on the sample. The adsorption was started, and the concentration of CO_2 leaving the adsorption column was recorded using a digital logger at one-minute intervals. The CO_2 concentration profile was presented in the form of C_t/C_0 against time. The breakthrough time is defined as the time when CO_2 reaches the end of the column and leaves with the other gas effluent (Gabelman, 2017), commonly determined at a 5% concentration (C_t/C_o = 0.05). The CO_2 adsorption capacity was then calculated.

3. Results and discussion

3.1 FESEM-EDX analysis

Figure 1 shows the results obtained from the FESEM-EDX analysis of the AC before and after the impregnation with 50 wt.% EW solution. Figure 1 (a and c) indicates that the surface and pores of the impregnated AC were partially covered by a thick layer, of what were assumed to be EW particles. This accumulation of EW particles on the AC surface and pores could be due to the use of a relatively high concentration of EW solution and the poor dispersion of the solution during impregnation. As a result, partially complete pore blocking was observed, as indicated by the apparent size of the surface pore openings reducing from a range of 4–10 µm to a range of 4–6 µm.

Conversely, the result of the EDX analysis shown in Figure 1 (b and d) reveals that the relative percentage composition of the oxygen (O) element in the EW-impregnated AC increased from 7.4 wt.% to 13.5 wt.%, and a new element was present (2.1 wt.% nitrogen (N)). This suggests that the EW was successfully impregnated onto the AC. Furthermore, the N element was prominently observed, which could aid the CO_2 adsorption, although this depends on the type of N-functionalities (Saha &

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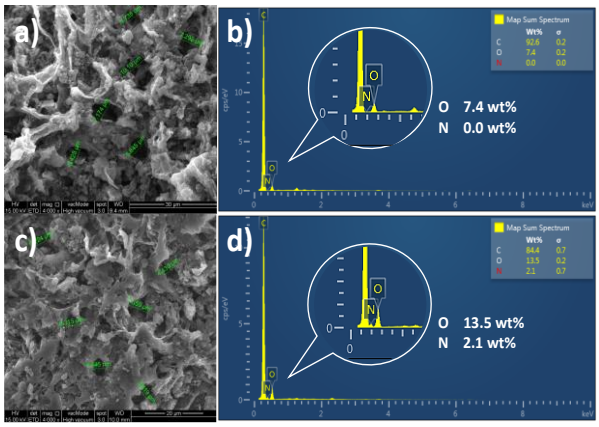

Figure 1. Results of FESEM-EDX analysis of palm shell-based activated carbon before (a and b) and after impregnation with 50 wt.% egg white solution (c and d).

Kienbaum, 2019). Further analysis is needed to validate this assumption.

3.2 Surface area and pore volume

The BET surface area analysis result revealed that the AC impregnated with 50 wt.% EW decreased in total surface area from 679 to 565 m^2/g. The t-plot micropore area also showed a reduction from 441 to 363 m^2/g. Meanwhile, the t-plot micropore volume decreased from 0.1798 to 0.1481 cm^3/g after the impregnation. However, all the reductions were below 18%, despite the higher concentration of EW used leading to the deposition of a thick layer of EW on the AC surfaces, thus blocking some of the micropores. These results agreed with the FESEM-EDX analysis.

3.3 FTIR analysis

Figure 2 displays the infrared spectra of palm shell AC before (top) and after (bottom) impregnation with 50 wt.% EW. All the absorption bands between 2662 cm^{-1} and 1589 cm^{-1} generated by both samples generally represent the peaks for the C-H stretching and aromatic ring vibration stretching (C≡C, C=C, C–O and C=O) of the AC (Rugayah, 2014). Meanwhile, the peaks between 3740 cm^{-1} and 3660 cm^{-1} may be attributed to the O-H stretching in hydroxyl groups or adsorbed water in the AC (Rugayah, 2014), which could be due to incomplete moisture removal during the analysis. Remarkably, the EW-impregnated AC revealed the presence of new peaks at 3557 cm^{-1}, 2957 cm^{-1}, and within a range of 1642 to 1514 cm^{-1}, confirming the existence of amide compounds in this EW-impregnated AC. The first two peaks from 1650 cm^{-1} to 1620 cm^{-1} were probably linked to C=O absorption of amide I and NH_2 deformation of amide II in primary amide, respectively (Parker, 1971). The peak near 1514 cm^{-1} could relate to the secondary noncyclic amide (amide II), while the peak at 3557 cm^{-1} indicates the stretching of free N-H of primary amide (Parker, 1971). Although the peak at 2957 cm^{-1} commonly represents the C-H stretching, it could also be interpreted as the band in free amines (Sashina et al., 2015). These findings confirmed that the EW was impregnated onto the AC. However, it is unclear whether this functional group was attached to the AC surface physically or chemically, unlike with the grafting method which is known to form covalent bonding with the grafted compound, but this would require a more advanced characterisation method.

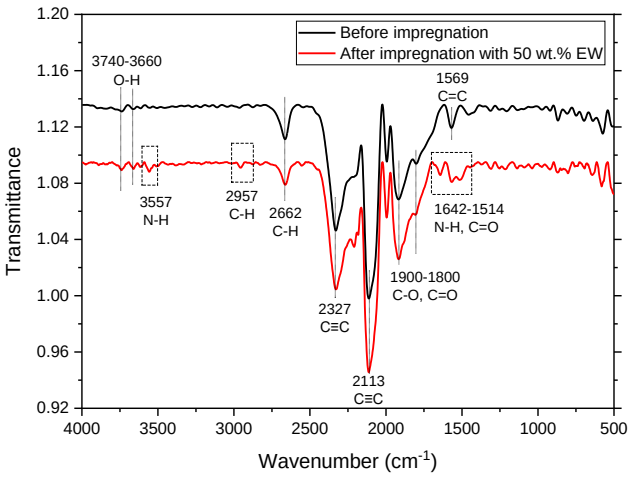

Figure 3. FTIR spectra of palm shell-based activated carbon before and after impregnation with 50 wt.% egg white solution.

3.4 Thermal analysis

Generally, the thermal properties of an adsorbent depend strongly on the stability of the material under heat treatment, and any modification to the material could alter its original properties. Therefore, thermal decomposition analysis can provide insightful information on the type of suitable application for which the material can be applied at its maximum allowable temperature. Figure 3 shows the thermal decomposition analysis of the 50 wt.% EW-impregnated AC. The initial weight loss of approximately 5% below 100 °C was due to the moisture loss of the sample. Depending on the type of feedstock, AC derived from biomass typically has high thermal stability above 500 °C (Sharma et al., 2021). In this study, the EW-impregnated AC lost 50% of its weight at 302 °C, as indicated by the onset degradation of the thermogravimetric curve (black) coinciding with a medium peak of the heat flow curve (blue) and the maximum endothermic peak

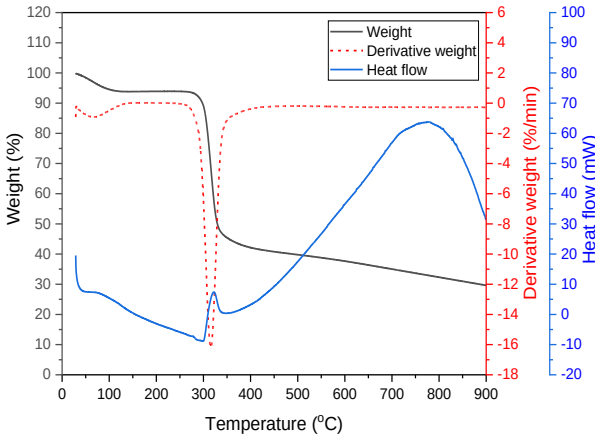

Figure 2. Thermal analysis of palm shell-based activated carbon after impregnation with 50 wt.% egg white solution.

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of the derivative weight curve (red). This could be attributed to the amino acids of the EW decomposing, which was reported between temperatures of 178 and 344 °C (Sashina et al., 2015). Similar results were observed in previous studies related to amino acid-incorporated adsorbents (Philip & Henni, 2023; Suhaili et al., 2023). At temperatures over 350 °C, the sample continued to degrade slowly, and about 28% of the weight remained at the end of the analysis (900 °C).

3.5 CO_2 adsorption performance

Figure 4 displays the CO_2 breakthrough curve for the AC before and after impregnation with 50 wt.% of EW. The results illustrate that the breakthrough time for the EW-impregnated AC was slightly longer (8.4 min) than its original performance (6.4 min). Furthermore, the steeper curve slope suggested an efficient mass transfer rate of the adsorbate throughout the packed-bed column (Gabelman, 2017). Meanwhile, the CO_2 adsorption capacity of the AC remained similar, with a minimal drop from 0.3204 mmol/g to 0.3029 mmol/g, most likely attributed to the significant reductions in the surface area and micropore volume after impregnation. Theoretically, physical impregnation means simply mixing the support and solution, whereby the solution monomer/polymer diffuses into the pores of the support materials without significant pore blockages (Jahandar Lashaki et al., 2019). Therefore, the surface area and pore volume reductions were normal, as reported in an amine-impregnated adsorbent (Gholidoust et al., 2017). However, these reductions may have compensated for the improved adsorption performance because the pores filled with additional functional groups that could adsorb more CO_2. In contrast, a very high solution concentration could lead to aggregation of the dried solution particles. In this case, EW attached onto the AC surface and blocked the pores, thus reducing the CO_2 accessibility to the amino acid functionalities inside the pores (Jahandar Lashaki et al., 2019). This could further explain the improved of breakthrough time of the EW-impregnated AC and the insignificant decline in its adsorption capacity. The EW-impregnated AC exhibited the longest breakthrough time compared with other waste-derived ACs, although further investigations are required to improve its adsorption capacity (Table 1).

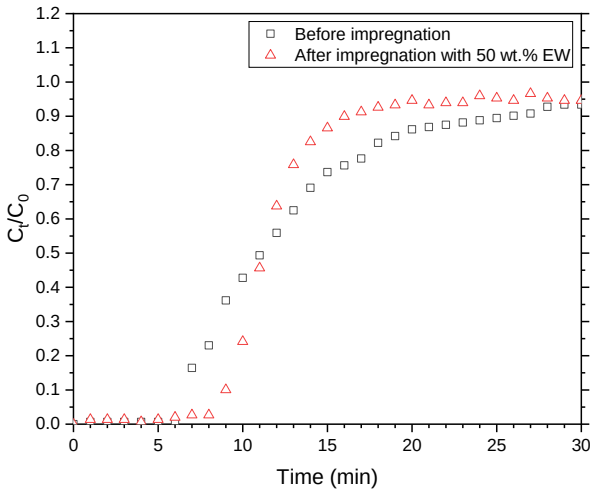

Figure 4. Breakthrough curve of CO_2 adsorption by palm shell-based activated carbon before and after impregnation with 50 wt.% egg white solution.

4. Conclusion

This study investigated CO_2 adsorption performance in correlation with the characteristics of palm shell-derived AC after impregnation with 50 wt.% of EW solution. The overall findings were promising, suggesting that EW could be an alternative green modifying agent to enhance the surface properties of AC. The successful impregnation of EW was clearly observed from the FTIR analysis results, with the presence of new peaks assigned to amide bands supported further by a 31% improvement in adsorption performance in terms of breakthrough time compared

Table 1. Comparison of CO_2 adsorption performance with other biomass/waste-derived activated carbons.

Adsorbent	Operating condition	Activation agent	Breakthrough time (min)	CO_2 adsorption capacity (mmol/g)	Reference
Palm kernel shell activated carbon	25°C, 1 bar	-	6.4	0.32	This study
	15% CO_2	50 wt.% egg white	8.4	0.30	
Palm kernel shell activated carbon	4 bar	-	< 0.1	0.54	Abdul Rani and Muda (2017)
	10% CO_2	10 wt.% CeO_2	5.8	0.63	
PET waste derived activated carbon	30°C, 1 bar	-	< 0.1	~0.55 (12.5% CO_2)	Kaur et al. (2019)
	5% CO_2	KOH to carbon (3:1)	3.2	0.55 1.33 (12.5% CO_2)	
Plastic derived activated carbon	15°C, 1 bar	-	< 0.1	0.14	Ligero et al. (2023)
	10% CO_2	KOH to carbon (2:1)	0.6	0.62 0.38 (30°C)	

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to raw AC. Thermal analysis also revealed that almost half the impregnated AC was decomposed at temperatures above 300 °C, which was related to the decomposition temperature of amino acid compounds. In terms of CO_2 adsorption capacity, the EW-impregnated AC performance was similar to that of raw AC, as inferred from the surface area and pore volume results, as well as the FESEM-EDX analyses. The surface area and pore volume reductions confirmed that the EW solution was filling the pores and deposited on the surface of AC surface; however, this was also found to cause a pore blockage phenomenon. While newly added amide functional groups of EW were successfully impregnated, as indicated by the FTIR analysis, some might have been completely blocked inside the AC pores. This left the remainder attached onto the outer surface layer of the AC and led to constant instead of improved adsorption capacity. Regardless, the EW-impregnated AC could still retain the CO_2 adsorbed on its surfaces for longer than the raw AC and other waste-derived activated carbons from the literature, indicating its potential as a new eco-friendly adsorbent. Future research could examine how to refine the method to optimise the adsorption capacity and the possible interaction mechanisms between this adsorbent and CO_2.

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