Synthesis and characterization of activated carbon/egg white composite as carbon dioxide adsorbent for green carbon capture

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Abstract. Global climate change has become a serious issue due to the increasing concentration of greenhouse gases, especially CO_2 emissions, which trigger global warming and extreme weather conditions. Carbon Capture and Storage (CCS) technology utilizing adsorption methods with activated carbon presents great potential as an economical and environmentally friendly solution. However, the use of chemical activators often raises environmental concerns, highlighting the need for natural alternatives such as soursop leaf extract, which contains bioactive compounds capable of introducing additional functional groups onto carbon surfaces. This research aims to develop an activated carbon composite from coconut shell activated with soursop leaf extract and modified with egg white to enhance CO_2 adsorption capacity. The research method was performed as follows: the extraction and phytochemical analysis of soursop leaves, synthesis of activated carbon/egg white (AC/EW) composites, and CO_2 adsorption assay. Material characterization was carried out using FTIR, SEM-EDX, BET nitrogen sorption, and PSA. The results showed that soursop leaf-activated carbon met the Indonesian National Standard (SNI). FTIR analysis revealed the appearance of new functional groups N-H and C-N indicating successful surface modification of the AC/EW composite. SEM-EDX analysis indicated enlarged pore morphology and the presence of nitrogen was 5.76%. BET nitrogen sorption analysis showed an increase in surface area up to 232.56 m^2/g after activation with soursop leaf extract. PSA results indicate that the composite particle size was in the microparticle range with an average of 691 nm. CO_2 adsorption tests demonstrated that the AC/EW composite powder with a 1:1 ratio showed optimal performance with an adsorption percentage of 68.36% and an adsorption capacity of 5.4353 mmol/g. This research successfully demonstrated the effectiveness of combining activated carbon with egg white protein in enhancing CO_2 adsorption while supporting green chemistry concepts through the utilization of sustainable organic waste.

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1 Introduction

Global climate change driven by the increasing concentration of greenhouse gases, especially carbon dioxide (CO_2) is a serious threat to the sustainability of life on Earth. Report National Oceanic and Atmospheric Administration (NOAA) records CO_2 concentrations in the atmosphere reached 414.7 ppm in 2021 [1]. Anthropogenic emissions from fossil fuel combustion and industrial activities have contributed to sea level rise, extreme weather events, and ecosystem disruption. Therefore, effective mitigation strategies such as carbon capture and storage (CCS) technologies are urgently required to reduce CO_2 emissions to the atmosphere [2].

Among various CCS techniques, adsorption using activated carbon has attracted significant attention due to its high surface area, well-developed porous structure, and excellent adsorption capacity. Rashidi et al. (2014) reported that coconut shell-based activated carbon exhibits a CO_2 adsorption capacity of 1.79 mmol/g, indicating its feasibility as a sustainable adsorbent material [3]. However, the adsorption performance of activated carbon is critically dependent on the activation process employed. Conventional chemical activation using strong bases such as NaOH or KOH can effectively enhance porosity, however these methods raise environmental concerns due to the corrosive nature and disposal challenges of these reagents. Recent studies have shown that wuluh starfruit extract can serve as an effective natural activator, successfully improving carbon adsorption capacity [4]. Similarly, soursop leaves present considerable potential as natural activators as they are rich in bioactive secondary metabolites including alkaloids, flavonoids, saponins, and phenolic compounds that containing functional groups that may contribute to surface chemistry modification [5].

Adsorbent modification is widely studied to enhance CO_2 adsorption performance. Hatta et al. (2023) reported that amino acid-modified activated carbon increased CO_2 adsorption capacity by up to 76% [6]. Gil-Lalaguna et al. (2022) demonstrated that pyrolysis-derived carbon from protein waste adsorbed approximately 40 mg/g of CO_2 [7]. However, many modification strategies rely on expensive commercial amine reagents, limiting their large scale applicability. Moreover, several studies have reported a reduction in surface area due to pore blockage after modification. Egg white, a protein-rich waste material containing abundant amine ($-NH_2$) functional groups, can serve as a low-cost and sustainable modification agent. As a Lewis base, the amine groups in egg white proteins ($-NH_2$) are expected to interact strongly with CO_2 as a Lewis acid potentially enhancing adsorption through chemisorption mechanisms.

Based on this background, this study innovates by utilizing coconut shells as a base material for activated carbon activated with soursop leaf extract and modified with egg white waste to produce an environmentally friendly adsorbent composite. The combined use of soursop leaf extract as a natural activator and egg white protein as a modifying agent composite for coconut shell-based activated carbon has not been systematically reported. Therefore, this research is positioned as a further development study aimed at improving adsorption performance using environmentally friendly materials. This green chemistry-based approach is expected to produce sustainable adsorbent materials with high CO_2 adsorption capacity while simultaneously supporting biomass waste valorization and greenhouse gas mitigation efforts.

2 Materials and methods

2.1 Materials and reagents

The materials used in this research are glass equipment, blender, magnetic stirrer, hot plate, grinder, manometer, oven, furnace, 2 cm × 1 cm cylinder mold, Fourier Transform Infra Red (PerkinElmer Spectrum IR 10.6.1), Brunauer-Emmet-Teller (Quantachrome Instrument NovaWin 11.06), Scanning Electron Microscope-Energy Dispersive X-Ray (JEOL JED-2300

Analysis), and Particle Size Analyzer (Malvern Zetasizer Advance Pro). The reagents used include coconut shell charcoal, soursop leaves (*Annona muricata* L.), egg white powder, distilled water, CO_2 gas, reagents for phytochemical screening, and universal pH.

2.2 Methods

2.2.1 Preparation of soursop leaf extract and phytochemical screening

The extraction process begins by making simplicia soursop leaves that are mashed into a powder. Extracts are obtained from soursop leaf powder and distilled water with a ratio of 1:10, then stirred using a magnetic stirrer for 1 hour with heating at a temperature of 60°C. The combination is cooled at room temperature and filtered so that filtrate is obtained as a brown soursop leaf extract. The next stage is to conduct phytochemical screening on soursop leaf extract. Qualitative phytochemical screening was conducted to identify alkaloids, flavonoids, saponins, quinones, tannins, and phenolic compounds. Alkaloids were tested using Mayer's and Dragendorff's reagents, indicated by white and orange precipitates. Flavonoids were identified using the Shinoda test, indicated by red, orange, or yellow coloration in the amyl alcohol layer. Saponins were detected using the foam test, where stable foam after the addition of 2 N HCl indicated a positive result. Quinones were identified by a red or orange color change after the addition of 1 N NaOH. Tannins and phenolics were detected using the $FeCl_3$ test, indicated by greenish-blue and dark green to blackish-green color changes.

2.2.2 Preparation of activated carbon with soursop leaf extract

Carbon is made from coconut shell charcoal which is crushed into small parts then mashed using a grinder until it becomes powder. Carbon powder placed in a crucible and a thermal activation process is carried out using a furnace at 600°C for 1 hour. After the furnace process, the carbon powder is activated using soursop leaf extract with a ratio of 1:10 and stirred using a magnetic stirrer for 2 hours by heating at a temperature of 60°C. The solution is soaked for 24 hours then vacuumed until there is no solution left and then dried in the oven at 60°C for 24 hours. Dried activated carbon is mashed and sifted again using a mesh sieve so that micro-sized activated carbon is obtained. The next stage is the activated carbon obtained by quality analysis based on SNI 06-3730-1995 including tests of moisture content, ash content, evaporative content, and pure activated carbon content.

2.2.3 Synthesis of activated carbon/egg white composites

The synthesis process begins with activated coconut shell carbon powder of soursop leaf extract mixed with egg white powder with composition variations of 1:1; 1:2; and 2:1. The mixture of the two powders is gradually added aqueduct to form a paste while stirring using a magnetic stirrer for 1 hour, then let it sit for 24 hours. After this stage, the activated carbon/egg white (AC/EW) composite is made into 2 forms, namely powder and disc. In powder-shaped AC/EW, the sample that has been left is then dried in the oven at 50°C for 42 hours, then mashed and sifted using a 200 mesh sieve so that a micro-sized composite powder is obtained. Meanwhile, in AC/EW in the form of disc solids, the sample is put in a cylindrical mold then put in an oven at 50°C for 42 hours.

2.2.4 Characterization and carbon dioxide adsorption testing

The AC/EW composite samples obtained were characterized using FTIR, SEM-EDX, BET, and PSA. Subsequently, a carbon dioxide (CO_2) adsorption test was conducted. The sample was placed into a glass tube and secured with cotton on both ends to prevent particle loss. The tube was then connected to the sample line, while a reference tube containing only cotton on both sides was connected to the reference line. CO_2 gas was introduced into the system at a constant flow rate of 0.5 L/min using a flow meter. All adsorption experiments were conducted at ambient temperature and atmospheric initial pressure. During the measurement, the sample tap was initially closed and the reference tap was opened and the pressure change indicated on the manometer was recorded as the reference pressure. Next, the reference tap was closed and the sample valve was opened and the corresponding pressure change was recorded. The difference in pressure change between the reference and sample measurements was used to determine the amount of CO_2 adsorbed by the sample. The adsorption capacity was calculated and expressed as the percentage of CO_2 absorbed. Each experiment was conducted in triplo and the average value was reported. A schematic of the experimental setup is shown in Figure 1.

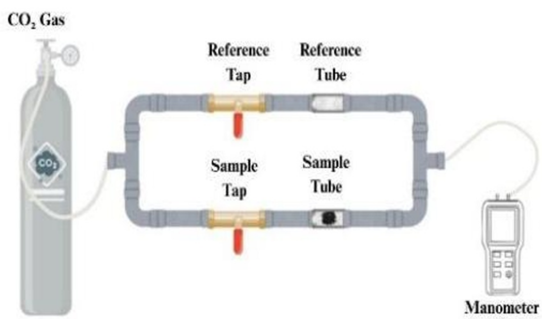

Fig. 1. Schematic of the carbon dioxide gas level measurement tool

3 Results and discussion

3.1 Soursop leaf extraction and phytochemical screening

Soursop leaf extraction has been carried out through the infundation method with the result in the form of a brownish-green solution with a yield of 54.75%. Soursop leaf extract was identified through phytochemical screening so that the results were obtained that positive soursop leaf extract contained secondary metabolite compounds in the form of alkaloids, flavonoids, saponins, tannins, quinones, and phenolics. These metabolite compounds are thought to have potential as environmentally friendly natural activating agents in activated carbon synthesis because they contain certain functional groups that can form new active sides on the carbon surface. These results are in accordance with those reported by Faradiba et al. (2024) that his research showed that soursop leaf extract contains secondary metabolites in the form of alkaloids, phenolics, saponins, quinones, and flavonoids [8]. The results of phytochemical screening of soursop leaf extract can be seen in Table 1.

Table 1. Results of phytochemical screening of soursop leaf extract

Metabolite compounds	Result	Information	Reference
Alkaloids	(+) (+)	Mayer: white precipitation Dragendorff: orange sediment	White and orange deposits (Oluyege et al., 2019)
Flavonoids	(+)	Yellow-orange	Yellow (Hartati et al., 2024)
Saponins	(+)	Foam formed	Foam formed (Hartati et al., 2024)
Tannins	(+)	Blackish blue	Green-blue (Oluyege et al., 2019)
Quinon	(+)	Brownish yellow	Orange (Hartati et al., 2024)
Phenolic	(+)	Blackish green	Blackish green (Oluyege et al., 2019)

3.2 Activated Carbon with Soursop Leaf Extract

The activation process is carried out through two stages, namely physics and chemistry. The physics stage is carried out by deep heating furnace which functions to remove water, volatile compounds and impurities that cover pores, as well as break hydrocarbon bonds so that the carbon surface area is larger [9]. The activated carbon yield from this stage reaches 97.40% due to the reduction in water content and organic compounds that evaporate during heating. The chemical stage is carried out by using soursop leaf extract as a natural activator to add functional groups on the surface of the carbon so that it can increase the adsorption capacity. The carbon yield before and after activation showed a visual difference, i.e. in coconut shell carbon (CSC) is deep black with a rough texture, while activated carbon with soursop leaf extract (ACSL) has a more faded color and smoother texture. This indicates that activation can change color and texture. The results of carbon activation are presented in Figure 2.

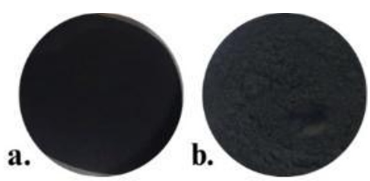

Fig. 2. Carbon powder (a) before activation (CSC), (b) after activation (ACSL)

3.3 Analysis of the Quality of Activated Carbon

The quality analysis aims to ensure the quality of the results of activated carbon synthesis whether it meets the acceptance standards based on SNI 06-3730-1995. The parameters tested included moisture content, ash content, evaporative substances, as well as pure activated carbon content. The results of these tests are presented in Table 2.

Table 2. Activated carbon quality test results

Test Parameters	Result	Unit	SNI Acceptance Requirements 06-3730-1995
Water content	1.05	%	Maximum 15%
Ash content	1.68	%	Maximum 10%
Volatility rate	0.34	%	Maximum 25%
Pure activated carbon content	97.98	%	Minimum 65%

The moisture content of activated carbon was obtained at 1.05% which still met the standard requirements, indicating that the amount of water left in the carbon pores was very small, resulting in more open pores thus increasing the adsorption capacity [10]. The ash content obtained at 1.68% which still meets the standard requirements indicates that most of the impurities in the form of metal oxides have evaporated during the heating process so that the pores of activated carbon become more open and the surface area increases [11]. The evaporative content obtained was 0.34% which met the standard indicating that the activated carbon produced has high stability and does not contain many volatile components that can interfere with adsorption performance [12]. The pure carbon content obtained was 97.98% which met the standard indicating that the activated carbon produced has high pure carbon so that the adsorption ability of the carbon can increase. The results of the analysis of activated carbon quality from the four parameters have met the criteria of SNI 06-3730-1995 so that the activated carbon obtained can be classified as good quality and suitable for use in various applications, especially as an effective adsorbent material.

3.4 Synthesis of Activated Carbon/Egg White Composites

In composites, activated carbon acts as the main reinforcing material (adsorbent) while egg whites act as a matrix capable of binding activated carbon particles. The results of the activated carbon/egg white composite can be seen in Figure 3.

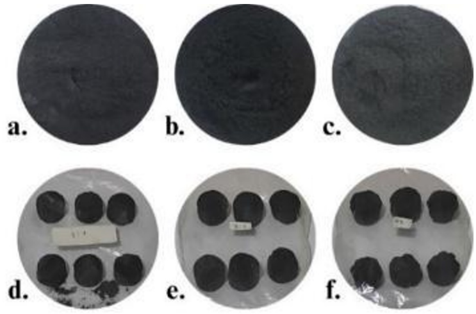

Fig. 3. AC/EW powder composite (a) 1:1, (b) 2:1, (c) 1:2, and AC/EW disc composite (d) 1:1, (e) 2:1, (f) 1:2

The AC/EW composite showed ratio-dependent physical characteristics in both powder and disc forms. In powders, the 2:1 ratio exhibited a deep black color due to the dominance of activated carbon, while the 1:2 ratio showed a lighter color as a result of higher egg white content, and the 1:1 ratio showing intermediate color intensity. In disc form, the 2:1 ratio produced a more compact and rigid structure, whereas the 1:2 ratio tended to be brittle and easily fractured. The 1:1 ratio showed relatively stable physical integrity during handling. These characteristics were evaluated qualitatively based on disc appearance, compactness, and resistance to breakage during preparation and handling. Overall, a higher activated carbon content contributed to improved structural integrity, indicating that ratio selection is important for obtaining a physically stable AC/EW composite suitable for CO_2 adsorption.

3.5 Characterization

The obtained AC/EW composites were characterized by FTIR to identify functional groups, SEM-EDX to analyze surface morphology and element components, BET to determine surface area and total pore volume, and PSA to determine particle size.

3.5.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR characterization was conducted to identify the functional groups prsent in coconut shell carbon (CSC), activated carbon from soursop leaf extract (ACSL), AC/EW composite, and egg whites (EW).

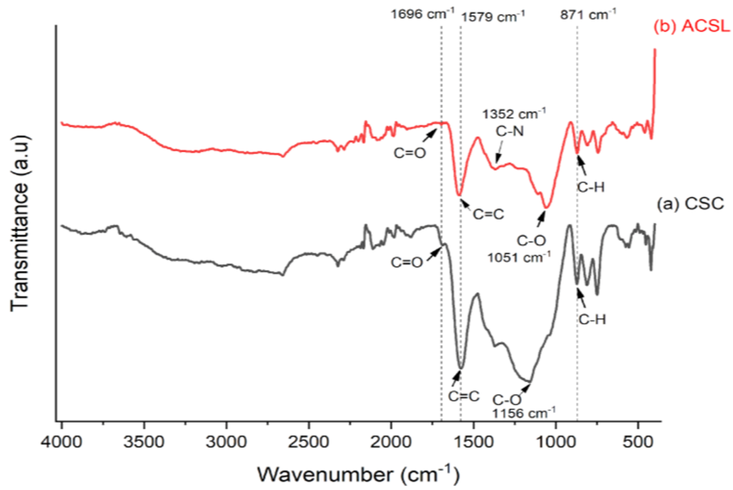

Fig. 4. FTIR spectrum of (a) coconut shell carbon (CSC) and (b) ACSL

The carbon FTIR spectrum (Figure 4a) shows typical absorption bands of functional groups, including aromatic C=C at 1579 cm^{-1} and C–O–C at 1156 cm^{-1}. The absorption band observed at 1696 cm^{-1} corresponds to the stretching vibration of the carbonyl (C=O) functional group. Although the peak intensity is relatively low, this phenomenon may be attributed to overlapping bands or partial reduction of oxygen-containing groups during the carbonization and activation processes. In activated carbon soursop leaf extract (Figure 4b), a new band appeared at 1352 cm^{-1}, namely the C–N group and a shift of C–O–C to 1051 cm^{-1} which indicated the addition of a nitrogen group from the bioactive compound of the soursop bioactive compound.

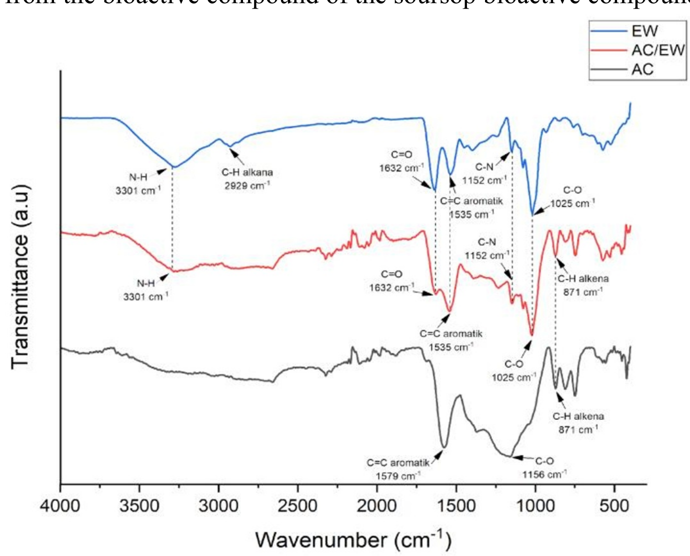

Fig. 5. FTIR spectrum from (a) egg white (b) AC/EW, (c) carbon

The egg white spectrum (Figure 5a) shows typical protein clusters, such as N–H vibration at 3301 cm^{-1}, aliphatic C–H strain at 2929 cm^{-1}, and carbonyl band (C=O) 1632 cm^{-1} and C–N at about 1152 cm^{-1}. This confirms the presence of nitrogen and oxygen that have the potential to interact with carbon. In the AC/EW composite (Figure 5b), the spectrum shows a combination of carbon and egg white characteristics. The N–H group remained detected at 3301 cm^{-1}, while band shifts of 1632 cm^{-1} (C=O) and 1535 cm^{-1} (aromatic C=C) showed an interaction between egg white proteins and carbon surfaces. The C–N bands at 1152 cm^{-1} confirm the nitrogen attachment of proteins, while the bands at 1025 cm^{-1} (C–O) and 871 cm^{-1} (C–H alkenes) show the aromatic structure of the carbon remains stable. These results prove that the synthesis process successfully forms composites, with chemical interactions between egg white protein groups and the surface of activated carbon, thus potentially improving the adsorption properties of the material.

3.5.2 Scanning Electron Microscopy-Energy Dispersive X-ray Spectroscopy (SEM-EDX)

SEM-EDX characterization was performed on pre-activation carbon samples (CSC), post-activation carbon using soursop leaf extract (ACSL), and activated carbon/egg white (AC/EW) composites. The results of the SEM analysis can be seen in Figure 6.

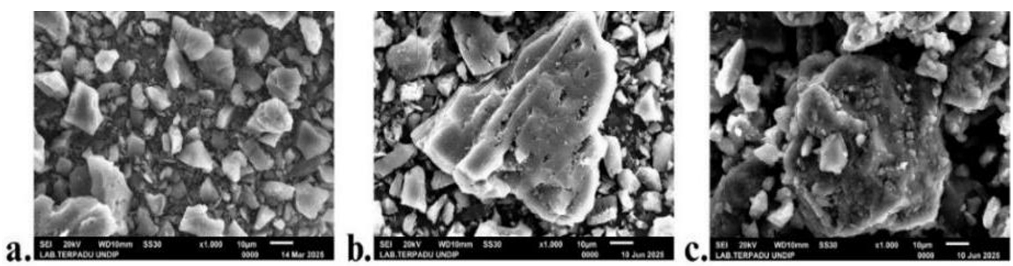

Fig. 6. Surface morphology using SEM in (a) CSC samples, (b) ACSL, and (c) AC/EW at 1000×

SEM analysis of all three samples showed clear morphological differences (Figure 6). CSC have tight surfaces and minimal pores due to pyrolysis residues. After activation with soursop leaf extract (ACSL), the surface becomes more open with pores starting to form which signals the role of soursop leaf bioactive compounds in opening up the pore structure. In AC/EW composites, the surface morphology is not homogeneous with large pores, and the presence of agglomerate structures that show the influence of egg white protein as a templating agent in the formation of micro and mesopori.

Table 3. Composition of elements in CSC, ACSL, and AC/EW samples

Elements	Mass (%)		
	CEC	ACSL	AC/EW
C	98.36	98.43	90.51
O	0.31	0.35	1.04
N	-	-	5.76

The EDX results support these findings (Table 3). CSC is dominated by carbon (98.36%) with very low oxygen (0.31%) indicating that the material is still pure and has minimal active groups. In ACSL, the carbon content was slightly increased (98.43%) accompanied by an increase in oxygen (0.35%) indicating the formation of new functional groups during activation. Meanwhile, in AC/EW the carbon content decreased (90.51%) with the emergence of nitrogen by 5.76%. Based on the results of the analysis of the three samples, it can be concluded that the AC/EW sample is the most potential material for CO_2 adsorption applications due to the combination of large porous structures that support rapid diffusion and the content of nitrogen functional groups that strengthen the interaction with CO_2.

3.5.3 Brunauer-Emmett-Teller (BET)

BET characterization was carried out on pre-activation carbon (CSC) and activated carbon samples of soursop leaf extract (ACSL) with the results presented in Table 4.

Table 4. Results of BET characterization in CSC and ACSL

Sample	Pore Surface Area (m^2/g)	Total Pore Volume (cc/g)	Average Pore Size (Å)
CSC	72.483	5.372×10^{-2}	14.8232
ACSL	232.568	1.123×10^{-1}	9.65311

The results of the BET analysis (Table 4) showed that the pre-activation carbon (CSC) had a surface area of 72.483 m^2/g, a pore volume of 5.372×10^{-2} cc/g, and an average pore size of 14.82 Å. After activation with soursop leaf extract (ACSL), the surface area increased significantly to 232.568 m^2/g and the pore volume to 1.123×10^{-1} cc/g, while the pore size decreased to 9.65 Å. An increase in surface area and pore volume indicates successful activation of opening and multiplying pores, while a decrease in pore size indicates the dominance of micropore structures that are effective for adsorption of small molecules such as CO_2. The activation mechanism using soursop leaf extract occurs predominantly through chemical activation, assisted by thermal treatment. Organic acid compounds in the extract act as natural activating agents that chemically interact with the carbon matrix during heating, promoting bond cleavage, partial oxidation, and the removal of tarry residues, which facilitates the formation and enlargement of micropores. Thermal activation further contributes by eliminating volatile compounds and impurities, enhancing pore accessibility. Consequently, ACSL exhibits superior textural properties compared to CSC, including higher surface area, larger pore volume, and a more suitable pore size distribution for efficient CO_2 adsorption.

3.5.4 Particle Size Analyzer (PSA)

PSA characterization was performed on activated carbon/egg white (AC/EW) composite samples to evaluate the extent to which the sample affected the size and uniformity of the particles with the results presented in Table 5.

Table 5. Particle size results in AC/EW samples

Parameters	Mean
Z-Average	691 nm
Polydispersity Index (PI)	0.5538

The results of PSA analysis (Table 5) show that the average particle size (Z-Average) of the AC/EW composite is 691 nm included in the microparticle category because it is >100 nm in size. This large size results from the agglomeration between activated carbon particles and egg white proteins in a composite structure. The polydispersity index (PI) value of 0.5538 is in the range of 0.10-0.70 indicating a homogeneous or monodispersed particle distribution. The results obtained show the size of the composite particles of AC/EW microparticles and have good distribution uniformity so that it supports a stable interaction with adsorbate in the CO_2 adsorption process.

3.6 Carbon Dioxide Adsorption Testing

Adsorption testing was carried out on 10 samples, namely black carbon (CSC), thermal method activated carbon (CSC-F), activated carbon activated from soursop leaf extract (ACSL), activated carbon/egg white composite (AC/EW) with composition variations (1:1; 2:1; 1:2) in the form of powder and disc, and egg white powder (EW) as control. The results of carbon dioxide adsorption are presented in Figure 7.

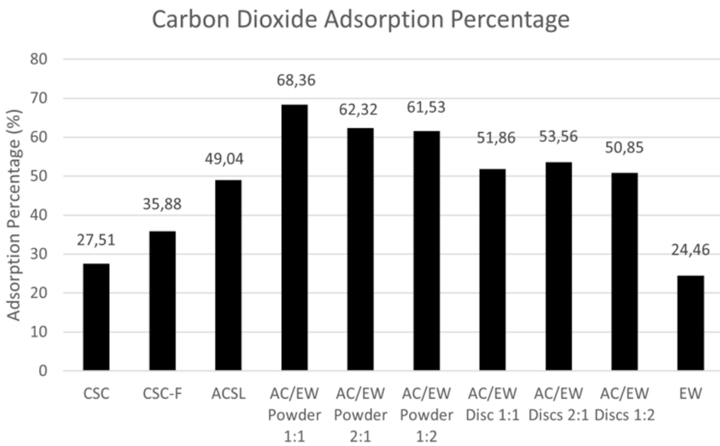

Fig. 7. Graph of CO_2 adsorption percentage

Based on Figure 7, the adsorption performance varies depending on the physical shape and composition ratio of the samples. Activation using soursop leaf extract significantly improves adsorption performance, as shown by the higher adsorption percentage of ACSL (49.04%) compared to CSC (27.51%) and CSC-F (35.88%). Among AC/EW composite samples, the 1:1 AC/EW powder sample had the highest adsorption percentage (68.36%) and the disc form, the adsorption value was lower with a ratio of 2:1 (53.56%). Powdered composites show better performance than discs because the surface area is larger so that they are easily accessible to CO_2 molecules. Egg white (EW) samples had the lowest percentage (24.46%), confirming the importance of the role of activated carbon in the adsorption process. The percentage of adsorption is related to the qe value which indicates the amount of mass of CO_2 absorbed per unit mass of the adsorbent. The qe value of each sample is presented in Table 6.

Table 6. Data on qe values and percentage of adsorption to CO_2

Sample Name	qe (mmol/g)	Adsorption Percentage (%)
CSC	2.1853	27.51
CSC-F	2.8501	35.88
ACSL	3.8971	49.04
AC/EW Powder 1:1	5.4353	68.36
AC/EW Powder 2:1	4.9539	62.32
AC/EW Powder 1:2	4.8909	61.53
AC/EW Disc 1:1	4.1219	51.86
AC/EW Discs 2:1	4.2568	53.56
AC/EW Discs 1:2	4.0410	50.85
EW	1.9429	24.46

Based on Table 6, there is a correlation between the percentage of adsorption and the value of adsorption capacity (qe). ACSL exhibits a higher qe value (3.8971 mmol/g) than CSC and

CSC-F, confirming the effectiveness of soursop leaf extract activation in increasing available adsorption sites. The 1:1 AC/EW powder sample that had the highest adsorption percentage also showed the highest qe value (5.4353 mmol/g), while the EW sample with the lowest percentage had the lowest qe value (1.9429 mmol/g). This confirms that the larger the CO_2 molecule that is absorbed, the higher the qe value and adsorption percentage. Based on this, the success of the AC/EW composite as a CO_2 adsorbent can be caused by a combination of physical adsorption mechanisms through activated carbon micropores and chemical adsorption. Furthermore, the modification of activated carbon with egg white protein, which acts as a Lewis base rich in amine groups, enhances CO_2 adsorption capacity through interactions with CO_2 as a Lewis acid. A 1:1 composition in powder form has been shown to be the most optimal because it provides a balance between the pore area of the activated carbon and the number of active groups of the protein.

4 Conclusion

Based on the results of the study, it can be concluded that the carbon from coconut shells was successfully activated using soursop leaf extract. The activated carbon is then modified with egg whites into a AC/EW composite that is effective as a CO_2 adsorbent. The test results showed that the 1:1 AC/EW composite in powder form had the best performance with an adsorption percentage of 68.36% and an adsorption capacity (qe) of 5.4353 mmol/g. Therefore, the modification of activated carbon using egg whites has been proven to be able to increase the adsorption capacity of CO_2 and has the potential to be applied as an environmentally friendly adsorbent material.

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