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Article

Synthesis and Characterization of Activated Carbon from Coconut Pulp via Physicochemical Activation and Its Potential for Biogas Purification

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Abstract

Coconut pulp is an abundant lignocellulosic byproduct with strong potential as a sustainable precursor for activated carbon (AC). This study synthesized and characterized coconut-pulp-derived AC via an integrated physicochemical route and assessed adsorption-relevant structural features for biogas upgrading (CO_2/H_2S). The process comprised carbonization at 400 °C, chemical activation with 3 N H_3PO_4 and 3 N KOH, followed by physical activation at 600 °C. Proximate analysis indicated low moisture (4.665%) and ash content (0.637%) with a yield of 12.38%, while the volatile fraction remained relatively high, consistent with the lignocellulosic nature of the precursor. The produced AC exhibited a BET surface area of 345.57 m²/g with a micropore-dominated structure, supported by an iodine number of 161.973 mg/g. FTIR spectra suggested the formation of stable aromatic structures after activation, and SEM observations revealed a well-developed pore network. As a key novelty, sequential dual chemical activation (H_3PO_4 + KOH) combined with subsequent physical activation was employed to enhance pore connectivity and carbon purity, which are critical for physisorption-driven adsorption. Overall, coconut-pulp-derived AC prepared via integrated physicochemical activation shows promising characteristics as a low-cost and sustainable adsorbent for biogas purification. Future work will quantify CO_2/H_2S adsorption performance using real or synthetic biogas streams and optimize activation parameters for scale-up.

Keywords: *Activated carbon, biogas, coconut pulp, CO_2 and H_2S adsorption, physicochemical activation*

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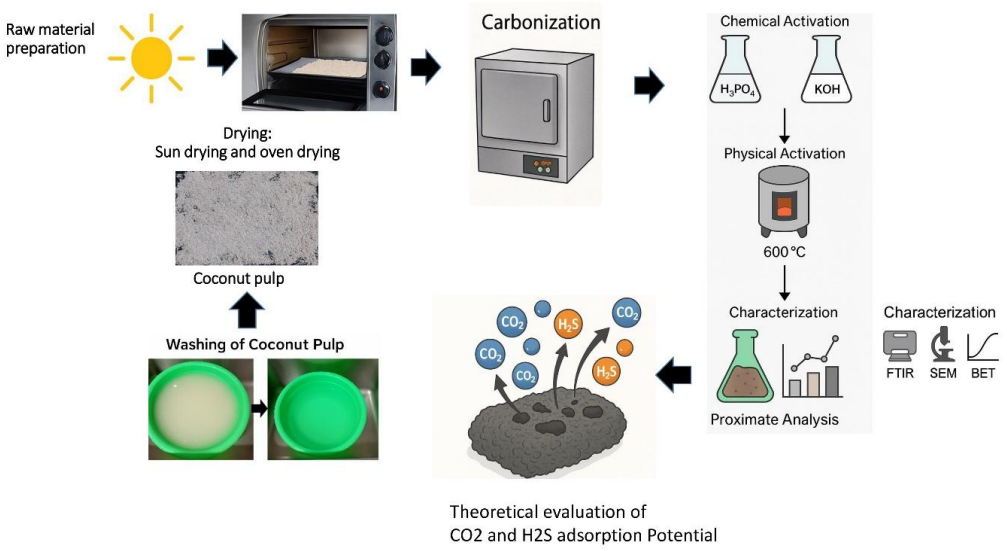
Graphical Abstract



Introduction

The utilization of renewable energy is a key pillar in the global transition toward sustainable energy systems. In Indonesia, the national medium-term development plan for 2025–2029 emphasizes energy independence through the sustainable use of local resources. Among various renewable energy sources, biogas has attracted significant attention due to its potential to simultaneously provide clean energy and support environmentally friendly waste management. Biogas is produced through the anaerobic fermentation of organic waste; however, raw biogas typically contains impurities such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). These contaminants are corrosive in nature, reduce the calorific value of biogas, and accelerate the degradation of energy conversion equipment, thereby limiting the widespread utilization of biogas without prior upgrading [1].

Various technologies have been developed for biogas upgrading, including absorption, membrane separation, and adsorption. Among these methods, adsorption using activated carbon is considered a relatively simple, cost-effective, and flexible approach, particularly when the activated carbon is synthesized from abundant and low-cost biomass residues [2,3]. Indonesia, as one of the world's largest coconut producers, generates substantial amounts of coconut-processing residues, including coconut pulp (or coconut dregs), which are rich in lignocellulosic components and therefore promising precursors for activated carbon production [4][5]. Previous studies have also reported that coconut-based residues exhibit favorable performance as raw materials for activated carbon in various adsorption applications [6].

Nevertheless, the performance of biomass-derived activated carbon is strongly influenced by the activation method employed. Recent studies have demonstrated that activated carbon produced from coconut pulp via single-step chemical activation using phosphoric acid (H_3PO_4) may exhibit an extremely high volatile matter content, reaching up to 94.86%, which far exceeds the national standard limit (SNI <25%). Excessive volatile matter can block active pores, hinder adsorbate diffusion, and ultimately reduce

gas adsorption efficiency [7]. In contrast, several studies have reported that the combination of chemical activation with physical or thermal activation can significantly enhance specific surface area, improve micro–mesopore distribution, and reduce volatile components, leading to improved adsorption performance for CO_2 and H_2S [2]. Further empirical evidence has shown that activated carbon derived from food industry residues can achieve CO_2 adsorption capacities of up to 495 mg g^{-1} under high-pressure conditions, highlighting the strong potential of biomass-based activated carbon for biogas purification applications [8].

However, systematic studies on the application of sequential dual chemical activation combined with subsequent physical activation for activated carbon derived from coconut pulp remain very limited. In particular, the relationships between integrated activation strategies, volatile matter reduction, pore structure development, and their implications for CO_2 and H_2S adsorption potential in biogas upgrading have not yet been comprehensively reported. This knowledge gap provides the scientific basis for the present study.

Accordingly, this study aims to synthesize activated carbon from coconut pulp through an integrated physicochemical activation approach and to evaluate its key physicochemical characteristics relevant to adsorption processes, including specific surface area, pore structure, and surface functional groups. In addition, the theoretical potential of the synthesized activated carbon for CO_2 and H_2S adsorption in biogas purification is assessed.

The novelty of this study lies in the first systematic application of sequential dual chemical activation using H_3PO_4 and KOH combined with subsequent physical activation on coconut pulp–derived activated carbon, as well as in the analysis of the relationship between volatile matter reduction and pore structure development in relation to gas adsorption potential. This approach is expected to produce activated carbon with superior quality compared to previously reported single-activation methods [2,7,8]. More broadly, this study contributes to the development of biomass-based adsorbent materials while supporting clean energy initiatives and sustainable agricultural waste management.

Materials and Methods

Materials and Instrumentations

Coconut pulp was used as the main precursor for activated carbon synthesis. Chemical reagents included phosphoric acid (H_3PO_4, 3 N), potassium hydroxide (KOH, 3 N), hydrochloric acid (HCl, 5%), iodine solution (0.1 N), potassium iodate (KIO_3, 0.1 N), potassium iodide (KI, 10%), sulfuric acid (H_2SO_4, 2 N), sodium thiosulfate ($Na_2S_2O_3$, 0.1 N), and starch indicator (1%). Distilled and deionized water were used throughout the experiments. The main instruments consisted of a muffle furnace, drying oven, mechanical shaker, FTIR spectrometer (Bruker Alpha II), scanning electron microscope equipped with EDX (JEOL JSM-6510LA), and BET surface area analyzer (Quantachrome Autosorb-iQ).

Synthesis of Coconut Pulp–Based Activated Carbon

Coconut pulp (1,043 g) was washed thoroughly with water to remove impurities and sun-dried until constant weight. The dried biomass was carbonized in a furnace at 400 °C for 2 h. The resulting char was ground and sieved to a particle size of 20 mesh prior to activation.

Sequential chemical activation was conducted by impregnating the char with 3 N H_3PO_4 (carbon-to-solution ratio 1:2, w/v) for 24 h at room temperature. The sample was then washed with distilled water until neutral pH and dried at 110 °C for 3 h [7]. Subsequently, alkaline activation was performed using 3 N KOH under the same impregnation ratio and duration, followed by washing and drying [9]. Physical activation was carried out by heating the chemically activated carbon at 600 °C for 1 h in a closed furnace, followed by natural cooling. The activated carbon was finally washed with deionized water to remove residual ash and dried at 110 °C [10].

Proximate Analysis and Iodine Number

Proximate analysis, including moisture content, volatile matter, ash content, fixed carbon, and yield, was performed according to the Indonesian National Standard (SNI 06-3730-1995). All measurements were conducted in triplicate, and average values were reported to ensure data reliability. The iodine adsorption capacity was determined using a standard titration method. Activated carbon samples (0.5 g) were contacted with standardized iodine solution under continuous shaking for 30 min, followed by filtration and back-titration using standardized $Na_2S_2O_3$ solution. Blank and sample titrations were performed in triplicate, and iodine numbers were calculated based on the difference between blank and sample titration volumes.

Characterization

Fourier Transform Infrared (FTIR) spectroscopy was used to identify surface functional groups of the activated carbon. Surface morphology and elemental composition were examined using SEM–EDX analysis. Textural properties, including specific surface area, pore volume, and pore size distribution, were evaluated using nitrogen adsorption–desorption isotherms based on the BET and BJH methods.

Data Processing and Reproducibility

All experimental measurements were performed at least three times, and results are presented as mean values. Data calculations were conducted using standard analytical equations, while graphical analyses were processed using spreadsheet software. Instrumental data (BET, FTIR, SEM–EDX) were analyzed using manufacturer-provided software. Reproducibility was ensured through consistent operating conditions and repeated measurements.

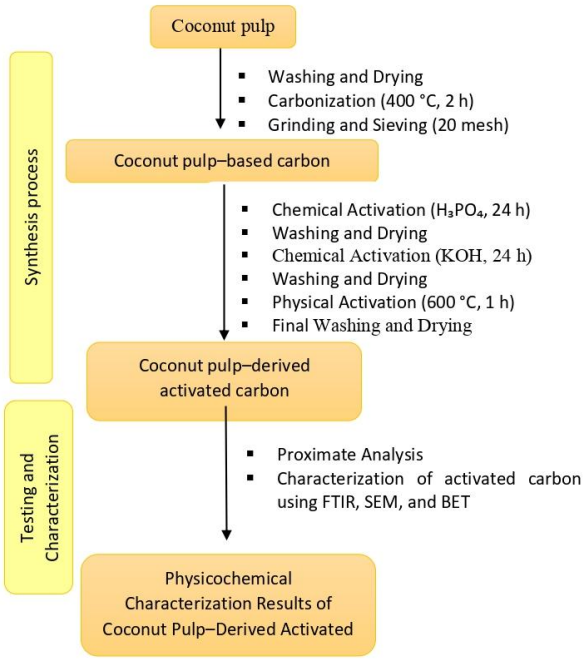


Figure 1. Flowchart of coconut pulp–derived activated carbon synthesis, testing, and physicochemical characterization.

Results and Discussion

Synthesis of Coconut Pulp-Based Activated Carbon

The use of coconut pulp biomass as a precursor for activated carbon offers an eco-friendly solution to reduce organic waste

while adding economic value. Activated carbon's high surface area and porous structure make it suitable for adsorption, purification, and energy applications. In this study, 1043 g of coconut pulp was processed through washing, drying, carbonization, and sieving. Washing eliminated impurities, while drying (sun and oven at 110°C) ensured moisture reduction for product stability [7].

Carbonization was performed at 400°C for 2 hours, which is sufficient for soft, low-density coconut pulp to undergo effective pyrolysis while preserving pore development [11]. Although higher temperatures enhance porosity [12], previous studies confirm that even at 400°C, chemically activated coconut residue can achieve surface areas up to 1187.61 m²/g with dominant microporosity.

The carbonized product was sieved through a 20-mesh screen to obtain particles suitable for adsorption applications, including biogas purification. This mesh size supports optimal CO_2 and H_2S adsorption while maintaining gas flow efficiency in fixed-bed systems. Similar results were achieved using banana stem-based activated carbon (CO_2 reduction 39.89%, CH_4 increased to 64.79%) [13] and tofu waste-based carbon (CH_4 up to 76.86%) [14], confirming the effectiveness of 20-mesh particle sizing

Activation of Coconut Pulp Carbon

Chemical activation using phosphoric acid (H_3PO_4) successfully produced activated carbon with a well-developed pore structure and high surface area. The introduction of phosphate-based polar functional groups enhanced the surface affinity for polar compounds such as H_2S, while also increasing CO_2 adsorption capacity through quadrupole interactions and micropore formation [15]. This was followed by alkaline activation using a 3N KOH solution, known for promoting micropore development and further increasing surface area.

Physical activation was subsequently conducted at 600°C for one hour in the absence of inert gas, aiming to open pore structures and eliminate volatile content. Although inert gas is commonly used to prevent oxidation, semi-closed furnace systems can still enable efficient activation, as supported by surface area values reaching 548 m²/g without inert protection [16]. High-temperature activation in such conditions may increase ash content due to the presence of inorganic minerals like Ca, Mg, and K. The resulting basicity of the carbon surface enhances interactions with acidic and polar gases such as H_2S and CO_2 [9]. Similar outcomes have been reported in studies where high surface pH improved adsorption performance despite the absence of inert gas [16]. In this study, the surface pH was measured at 13–14, indicating substantial ash content. As a preventive measure, deionized water washing was applied to reduce residual ash, prevent pore blockage, and maintain optimal adsorption efficiency.

Proximate Analysis

Proximate analysis evaluates key biomass properties moisture, ash, volatile matter, and fixed carbon that influence thermal stability, chemical reactivity, and micropore formation. These parameters are critical for determining biomass suitability as a precursor to activated carbon, as they directly affect adsorption capacity and carbon yield [17].

Yield Determination (SNI 06-3730-1995)

The yield of activated carbon is a key indicator of the efficiency of biomass conversion into porous materials with high adsorption potential. From 485.45 g of dried coconut pulp, 60.11 g of activated carbon

was obtained after carbonization, chemical activation with H_3PO_4 and KOH, and physical activation at 600°C, resulting in a final yield of 12.38%. Using dry mass as the calculation basis aligns with standard practice in biomass-based activated carbon production, as only the solid fraction contributes to carbonization and pore formation. This approach ensures greater accuracy and consistency across studies, avoiding bias from variable moisture content [18].

The obtained yield is consistent with the range of 11.2–14.63% reported for coconut residues [19]. Low yields are typically caused by mass loss during carbonization and thermal degradation of organics, particularly due to low lignin content. Nonetheless, yield reduction is often accompanied by improved pore development and surface area expansion, enhancing adsorption performance for applications such as water purification and CO_2 and H_2S capture [6].

Table 1. Presents the comparative proximate analysis of dried coconut pulp, chemically activated coconut pulp carbon, and combined chemical–physical activation, following the Indonesian National Standard (SNI 06-3730-1995).

Sample	Moisture content (%)	Ash content (%)	Volatile matter content (%)	Fixed carbon content (%)
Dried coconut pulp	1.352	0.834	98.946	0.220
Coconut pulp activated carbon-chemical	6.179	8.651	89.316	2.033
Coconut pulp activated carbon-chemical-physical	4.665	0.637	97.485	1878
SNI 06-3730-1995	Max 15	Max 10	Max 25	Min.65

Moisture Content Determination (SNI 06-3730-1995)

Moisture content is a critical parameter in activated carbon characterization, as it directly affects storage stability, adsorption efficiency, and susceptibility to microbial growth. In this study, the measured moisture contents were 1.352% for dried coconut pulp, 6.179% for chemically activated carbon (H_3PO_4–KOH), and 4.665% for chemically–physically activated carbon, all well below the SNI maximum limit of 15%.

The low value for dried coconut pulp indicates effective initial dehydration, while the higher level in chemically activated samples is attributed to the hygroscopic nature of KOH and moisture uptake during immersion and washing. In contrast, the lower value in chemically–physically activated carbon suggests that high-temperature thermal activation effectively removed residual water, enhancing stability.

These findings are consistent with [20], who reported 9.57% moisture in natural coconut fibers, higher than the values obtained in this study, underscoring the efficiency of the applied activation and drying methods. Low moisture content in activated carbon has been reported to enhance shelf life and adsorption performance. In this study, the low moisture level indicates successful activation and drying processes, supporting the potential of coconut pulp-based activated carbon for water and gas purification applications [21].

Determination of Volatile Matter Content (SNI 06-3730-1995)

Coconut pulp, a by-product of coconut milk extraction, contains 47.18% cellulose, 12.10% hemicellulose, and 10.58% lignin [5]. Its soft parenchymal structure contributes to low density and a high surface area, accelerating thermal decomposition during carbonization. The low activation energies of cellulose and hemicellulose [22] explain the high volatile matter content recorded at different stages: 98.946% in raw coconut pulp, 89.316% after chemical activation, and 97.485% following combined chemical–physical activation. These results are consistent with [7], who reported 94.860% volatile matter in phosphoric acid-activated coconut pulp-based carbon.

The decrease to 89.316% after chemical activation confirms the effectiveness of KOH as a dehydrating and oxidizing agent. KOH facilitates the removal of non-carbonaceous substances, promotes aromatic structure formation, and supports micropore development, enhancing thermal stability and surface area for adsorption [23].

Combined activation showed a less significant reduction to 97.485%, likely due to limited pyrolysis efficiency under semi-closed conditions without inert gas [16]. All samples still exceeded the SNI 06-3730-1995 volatile matter threshold of 25%, indicating the need for further optimization in activation parameters.

High volatile content, however, may benefit adsorption by introducing active functional groups like –OH, –COOH, and –C=O, which facilitate interactions with polar gases such as CO_2 and H_2S. Alkaline activation not only reduces volatile matter but also improves carbon structure and enhances microporosity and adsorption capacity [6].

Determination of Ash Content (SNI 06-3730-1995)

Ash content represents the residual inorganic compounds remaining after combustion and is a key determinant of activated carbon quality and purity, particularly due to elements such as silica, calcium, and magnesium that are resistant to thermal degradation [24].

The analysis showed that dried coconut pulp contained 0.834% ash, which increased to 8.651% after chemical activation but decreased to 0.637% following combined chemical–physical activation. All values remained below the maximum threshold of 10% set by SNI 06-3730-1995. The higher ash content in chemically activated samples is likely attributed to residual inorganic salts such as K_2CO_3 and K_2O from insufficient washing of KOH, while efficient washing has been reported to reduce ash content and enhance carbon purity [25]. Elevated ash content may also indicate the deposition of minerals on the carbon surface or within its pores, potentially hindering adsorption performance. Therefore, maintaining low ash content is not only critical to meeting quality standards but also to ensuring the performance and chemical stability of activated carbon.

Determination of Fixed Carbon Content (Based on SNI 06-3730-1995)

The fixed carbon content of coconut residue-based activated carbon was evaluated based on the Indonesian National Standard (SNI 06-3730-1995), which stipulates a minimum of 65% as a quality benchmark. In this study, all samples recorded fixed carbon levels below the standard, indicating incomplete carbonization due to high volatile matter. Despite this, a high volatile fraction can promote pore development and enhance surface chemistry through the formation of

–OH, –COOH, and –C=O groups, which improve interactions with polar compounds.

Activated carbon with substandard fixed carbon levels has previously shown high adsorption efficiency for iron ions, attributed to oxygenated functional groups generated during carbonization [7]. Similar observations were made by previous study [26], who reported that highly porous and chemically active carbon materials achieved superior greenhouse gas adsorption compared to commercial activated carbon, regardless of fixed carbon content.

These results suggest that, although the samples did not meet the fixed carbon requirement, their porous structure and functionalized surfaces still provide significant potential for adsorption applications. A comprehensive assessment of activated carbon quality should therefore include surface area, porosity, and chemical functionality alongside fixed carbon content.

Iodine Number Determination

Activated carbon is widely used to remove harmful gases like CO_2 and H_2S, with the iodine number (mg I_2/g) serving as a key indicator of micropore content and adsorption capacity. Experimental data (Table 2) showed variations in iodine uptake across the three samples

Table 2. Iodine adsorption capacity of various activated carbon samples

Sample	Iodine adsorption capacity (mg/g)
Dried coconut pulp	141.057
Coconut pulp activated carbon-chemical	209.003
Coconut pulp activated carbon-chemical-physical	161.973

The elevated iodine number recorded in the chemically activated coconut pulp sample confirms the superior efficacy of chemical activation in enhancing surface area and promoting micropore formation. This aligns with findings by [26], which indicate that biomass-derived activated carbons with high iodine values exhibit enhanced adsorption of toxic and greenhouse gases.

Micro- and mesopores play a critical role in the physisorption of small gas molecules such as CO_2 and H_2S. The adsorption behavior varies with molecular polarity; H_2S, being polar, and CO_2, non-polar, require optimized pore architecture and sufficient surface area for effective capture.

With an iodine number exceeding 209.003 mg/g, the chemically activated coconut pulp carbon exhibits strong potential for application in air purification systems, particularly for mitigating CO_2 and H_2S emissions from industrial and organic waste sources. Its high adsorption capacity and modifiable surface chemistry position it as a viable material for advanced selective adsorbents or catalytic support platforms.

IR-Spectroscopy of Activated Carbon

FTIR analysis was performed to evaluate changes in surface functional groups resulting from chemical and physical activation of coconut pulp–derived carbon. The FTIR spectra of dried coconut pulp, chemically activated carbon, and chemically–physically activated carbon are presented in Figure 2. Figure 2 shows that dried coconut pulp exhibits typical lignocellulosic features, characterized by a broad –OH stretching band around 3400 cm^{-1} and a C=O stretching band near 1740 cm^{-1}, indicating the presence of hydroxyl and carbonyl groups associated with cellulose and hemicellulose.

Following chemical activation, notable spectral changes were observed. The

intensity of –OH and C=O bands markedly decreased, indicating the decomposition of oxygen-containing functional groups. In addition, the emergence of absorption bands in the 750–880 cm^{-1} region suggests the formation of substituted aromatic structures, reflecting increased aromaticity of the carbon framework. These changes indicate that chemical activation effectively reduces polar functional groups while promoting aromatic domain development.

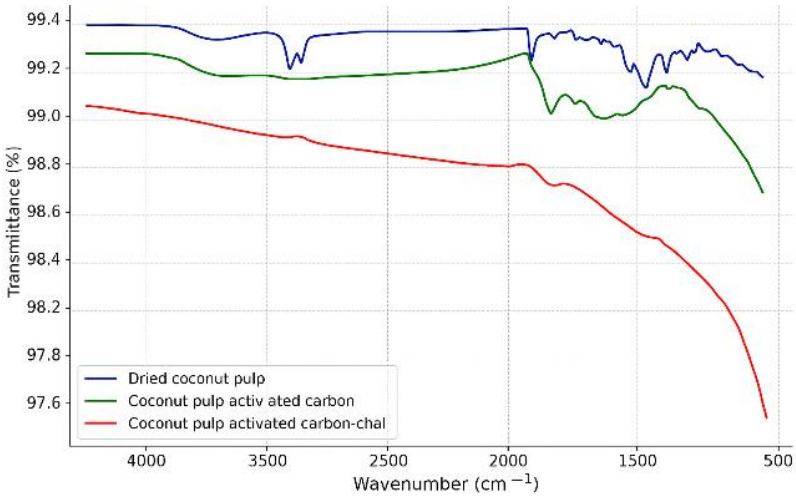


Figure 2. FTIR spectra of dried coconut pulp, coconut pulp activated carbon-chemical, and coconut pulp activated carbon-chemical- physical, showing the transformation of functional groups during the activation process.

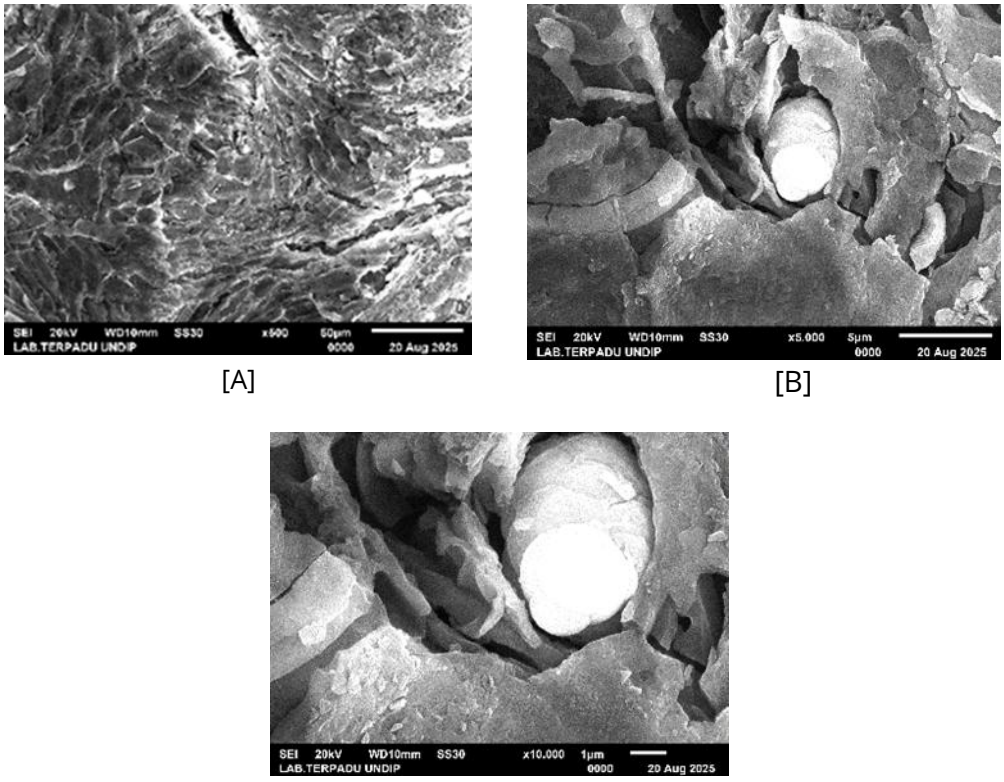
Further modification was evident in the chemically–physically activated sample, where the –OH and C=O bands were further diminished and a distinct band near 900 cm^{-1} appeared, attributed to aromatic =C–H vibrations. This progressive reduction of polar groups and enhancement of aromatic structures suggest more extensive devolatilization and structural rearrangement during combined activation.

These spectral transformations are consistent with previous studies on coconut-based activated carbons, which reported that activation processes reduce hydroxyl and carbonyl functionalities while enhancing aromatic character due to hemicellulose and lignin degradation [27]. Similar FTIR behavior was also observed for H_3PO_4-activated coconut residue–based activated carbon, where the formation of aromatic =C–H structures was correlated with improved adsorption performance [7]. Overall, the FTIR results confirm that integrated chemical–physical activation effectively modifies surface chemistry by decreasing polarity and increasing aromaticity, which is favorable for adsorption applications.

Morphological of Activated Carbon

SEM–EDX analysis was conducted to investigate the pore morphology and chemical composition of dried coconut pulp, coconut pulp activated carbon-chemical, and coconut pulp activated carbon-chemical-physical. SEM images at 500× magnification (Figure 3.a) revealed that the dried coconut pulp sample exhibited a rough surface dominated by macropores, which likely formed due to the evaporation of volatile compounds during carbonization. At a medium magnification of 5000× (Figure 3.b), the emergence of mesopores was observed, serving as transitional diffusion pathways. However, at higher magnification (10,000×; Figure 3.c), only a few micropores were visible, with uneven distribution. These

findings are consistent with [28], who reported that physically activated coconut shell-based carbon typically contains macropores in the range of 0.8–1.0 μm and exhibits limited micropore distribution.



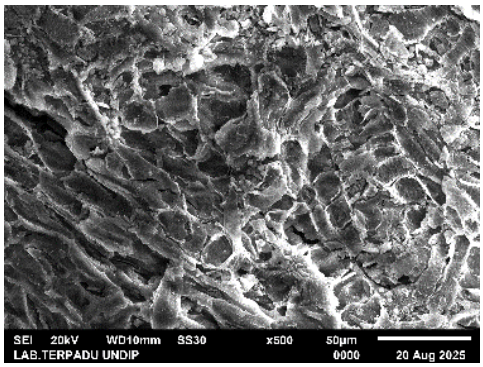
[A] [B]

[C]

Figure 3. SEM images of dried coconut pulp at different magnifications: 500× [A], 5000× [B], 10,000× [C].

SEM analysis of chemically activated coconut pulp carbon showed a more open surface, thinner pore walls, and well-developed meso- and micropores. The presence of fine particles suggested residual activating agents. This observation is in line with the findings of [29], who reported that KOH activation enhances pore quantity and connectivity but tends to leave behind mineral residues such as K_2O. EDX results further support this, showing a carbon composition of 69.44% (PURE) and 88.16% (OXIDE), along with a relatively high potassium content of 5.72% (PURE) and 10.65% (OXIDE).

The coconut pulp activated carbon-chemical-physical exhibited the most optimal characteristics among the samples. SEM images at various magnifications revealed a well-organized hierarchical pore structure consisting of macropores serving as primary transport channels, mesopores facilitating molecular diffusion, and densely distributed micropores. This sponge-like structure indicates a high specific surface area and excellent pore connectivity. These findings are consistent with [30], who reported that combined activation methods can produce activated carbon with high porosity and hierarchical structures that enhance molecular diffusion. EDX analysis further supports these results, showing dominant carbon content (89.48% PURE; 96.65% OXIDE), moderate oxygen content (8.23%), and very low levels of residual mineral elements.



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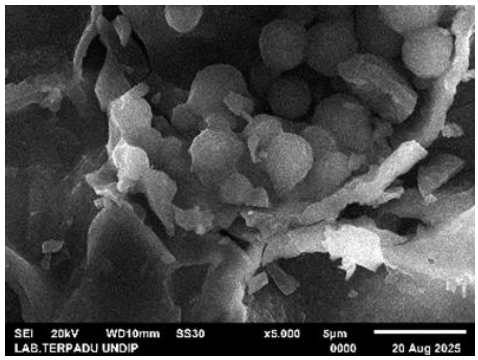

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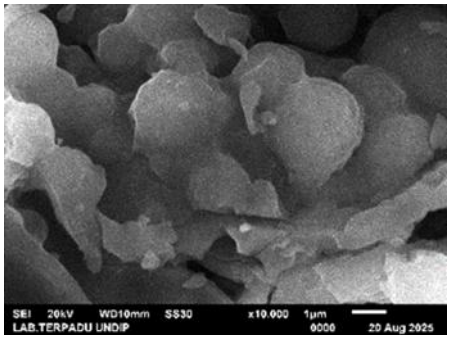
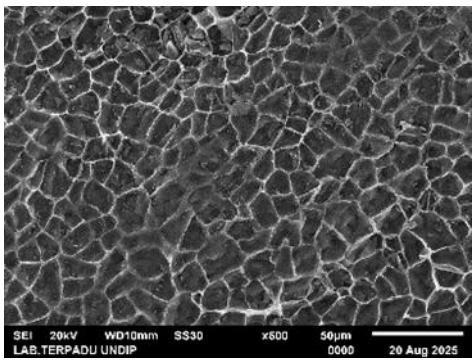


[C]

Figure 4. SEM images of coconut pulp activated carbon-chemical at different magnifications: 500× [A], 5000× [B], 10,000× [C].



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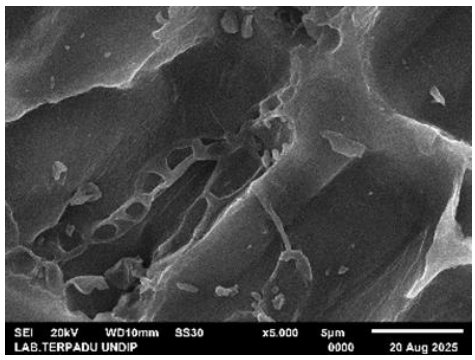

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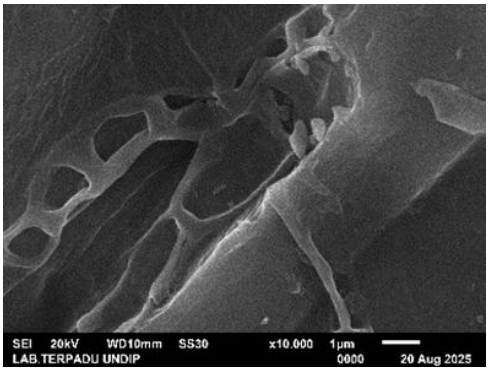

[C]

Figure 5. SEM images of coconut pulp activated carbon-chemical-physical at different magnifications: 500× [A], 5000× [B], 10,000× [C].

Comparatively, the dried coconut pulp exhibits superior carbon purity but retains a relatively simple pore structure. The coconut pulp activated carbon-chemical shows improved pore development and the presence of polar functional groups; however, it also presents a decline in purity due to potassium residue. In contrast, the coconut pulp activated carbon-chemical-physical offers the most balanced characteristics—exceptionally high carbon purity, an optimized hierarchical pore structure, and minimal residual mineral content. These findings are not only consistent with previous literature but also affirm that the combined activation method is a superior approach for producing high-quality activated carbon in terms of both structural morphology and chemical composition

Surface Textural Analysis Using BET–BJH Methods

The textural properties of coconut pulp–derived carbon were evaluated using BET–BJH analysis, as summarized in Table 3. The dried coconut pulp sample exhibited a relatively high specific surface area of 245.72 m^2/g, dominated by microporous structures (200.70 m^2/g) with an average pore size of 2.085 nm. This behavior is consistent with previous reports indicating that lignocellulosic coconut residues inherently promote micropore formation during carbonization due to the decomposition of cellulose, hemicellulose, and lignin components [5,11].

In contrast, the coconut pulp–derived carbon subjected solely to chemical activation exhibited a significant reduction in BET surface area (10.47 m^2/g) and total pore volume, accompanied by an increase in average pore size to 7.262 nm. This decrease can be scientifically explained by pore blockage and limited pore accessibility caused by residual activating agents and volatile compounds that were not completely removed in the absence of subsequent physical activation.

Table 3. Textural properties of activated carbon based on BET and BJH analyses (values reported as mean ± standard deviation, n = 3).

Sample	BET surface area (m^2/g)	Total pore volume (cc/g)	Average pore size (nm)	Micropore surface area (m^2/g)	Micropore volume (cc/g)
Dried coconut pulp	245.72	0.1281	2.085	200.70	0.0808
Coconut pulp activated carbon-chemical	10.47	0.01901	7.262	3.352	0.001468
Coconut pulp activated carbon-chemical-physical	345.57	0.1595	1.846	282.80	0.1059

Previous studies have reported that chemical activation using strong activating agents such as phosphoric acid or alkaline compounds may lead to the formation of inorganic residues and tarry by-products, which can partially occupy pore channels and suppress nitrogen adsorption, resulting in artificially low BET surface area values [7,9].

Furthermore, chemical activation without high-temperature thermal treatment may induce pore widening rather than effective pore development, shifting the pore structure from microporous to mesoporous domains. This phenomenon explains the drastic decrease in micropore surface area (3.352 m^2/g) observed for the chemically activated sample. Similar trends have been reported in coconut-based activated carbons, where insufficient thermal activation led to reduced microporosity due to incomplete removal of activating residues and unstable pore structures [10,19].

By comparison, the coconut pulp–derived activated carbon produced through combined chemical and physical activation exhibited the highest BET surface area (345.57 m^2/g) and micropore contribution (282.80 m^2/g), with a reduced average pore size of 1.846 nm. The subsequent physical activation at 600 °C effectively removed residual activating agents, promoted devolatilization, and reopened blocked pores, resulting in a well-developed and interconnected microporous structure. The critical role of physical activation in enhancing pore accessibility and stabilizing pore architecture has been widely reported for biomass-based activated carbons [3,10, 25].

Overall, the observed reduction in BET surface area for the chemically activated sample does not indicate inferior material quality, but rather reflects limited accessible porosity due to residual chemical species and the absence of sufficient thermal activation. The substantial recovery and enhancement of surface area achieved through integrated chemical–physical activation confirm that dual activation strategies are essential for producing high-quality activated carbon with enhanced microporosity, which is particularly beneficial for gas adsorption applications such as CO_2 and H_2S removal from biogas [2,8].

Evaluation of Adsorption Potential of Coconut Pulp–Derived Activated Carbon for CO_2 and H_2S Removal in Biogas

Activated carbon synthesized from coconut pulp residue exhibits strong potential as an adsorbent for biogas purification, particularly for the removal of carbon dioxide (CO_2) and hydrogen sulfide (H_2S). This evaluation is based on an integrated analysis of surface textural properties (BET–BJH), surface chemistry (FTIR), iodine number, and supporting morphological evidence (SEM–EDX). These parameters are widely recognized as key indicators governing gas adsorption performance in porous carbon materials.

Surface textural analysis demonstrated that the chemically and physically activated carbon possessed a high BET specific surface area of 345.57 m^2/g, with a dominant micropore surface area of 282.80 m^2/g. The prevalence of microporosity is particularly advantageous for the adsorption of small gas molecules such as CO_2 (kinetic diameter ≈ 0.33 nm) and H_2S (≈ 0.36 nm), which preferentially adsorb within narrow micropores. Previous studies have shown that activated carbon with a well-developed microporous structure can achieve very high CO_2 removal efficiency under optimized adsorption conditions, highlighting the

crucial role of micropore-dominated surface area in gas separation processes [31].

The adsorption potential inferred from BET analysis is further supported by the iodine number of 161.973 mg/g, which quantitatively reflects the abundance of accessible micropores. High iodine numbers are commonly associated with enhanced adsorption capacity, as iodine molecules predominantly occupy microporous regions. A positive correlation between iodine number and adsorption performance has also been reported for biomass-derived activated carbons, confirming that higher iodine uptake corresponds to increased gas adsorption efficiency [32]. In this study, the consistency between high BET micropore surface area and iodine number strongly indicates favorable adsorption characteristics.

FTIR analysis provides complementary insight into the surface chemistry governing adsorbate–adsorbent interactions. The observed reduction in polar functional groups such as hydroxyl (–OH) and carbonyl (C=O), along with the formation of aromatic C=C bonds, suggests increased surface hydrophobicity and structural stability. A less polar surface is beneficial for selective adsorption of non-polar or weakly polar gases such as CO_2 and H_2S, as it minimizes competitive adsorption with water vapor. Similar FTIR characteristics have been reported to significantly enhance H_2S adsorption performance in chemically modified coconut shell–based activated carbons [33].

Morphological analysis using SEM revealed a hierarchical pore structure consisting of interconnected macro-, meso-, and micropores, which facilitates gas diffusion toward active adsorption sites. EDX analysis confirmed a high carbon content of 96.65%, indicating minimal inorganic residue that could otherwise block pore channels. Comparable structural features and high carbon purity have been reported for biomass-based activated carbons exhibiting surface areas exceeding 400 m²/g and superior gas adsorption behavior [34].

From an application perspective, activated carbon has been demonstrated to significantly improve biogas quality by increasing methane (CH_4) concentration to approximately 91.6% while reducing CO_2 levels below 14% using adsorption columns arranged in series [35]. Considering the high micropore surface area, elevated iodine number, and favorable surface chemistry observed in this study, coconut pulp–derived activated carbon is expected to exhibit comparable adsorption performance. These results confirm that the material is technically suitable and economically promising for sustainable biogas upgrading applications.

Conclusion

Activated carbon derived from coconut pulp waste was successfully synthesized through an integrated chemical–physical activation strategy, resulting in significant enhancement of physicochemical properties relevant to gas adsorption. The combined activation approach effectively developed a well-connected hierarchical pore structure, as evidenced by a high BET specific surface area of 345.57 m²/g and a dominant micropore surface area of 282.80 m²/g, which are particularly favorable for the adsorption of small gas molecules such as CO_2 and H_2S. The high carbon purity (96.65%), iodine number (161.973 mg/g), low ash content (0.637%), and moderate moisture content (4.665%) further confirm the high quality and structural stability of the synthesized activated carbon. Scientifically, this study demonstrates that sequential dual

chemical activation followed by physical activation is an effective strategy to overcome pore blockage and limited microporosity associated with single-step activation, thereby strengthening the structure–property relationship of biomass-based adsorbents. From an application perspective, the results highlight the strong potential of coconut pulp–derived activated carbon as a sustainable and low-cost adsorbent for biogas upgrading. Nevertheless, this study is limited to physicochemical indicators of adsorption performance; therefore, future work should focus on dynamic adsorption experiments using real or simulated biogas to evaluate adsorption capacity, selectivity, and long-term regenerability under practical operating conditions.

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Author Contributions

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Conflict of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

[1] Asadollahzadeh, P., Hamedi, M. H., and Jazayeri, S. A., "Investigation of Biogas Composition Effects on Combustion Characteristics of an RCCI Engine. *Gas Processing Journal.* 2020. 8(2): 61-67. http://10.22108/gpj.2020.123076.1086

[2] Santos-Clotas, E.,Cabrera-Codony, A., Ruiz, E., Fuente, B., and Martín, M. J., "Sewage Biogas Efficient Purification by Means of Lignocellulosic Waste-Based Activated Carbons. *Bioresource Technology*. 2019. 275: 207–215, https://doi.org/10.1016/j.biortech.2018.12.060

[3] Sawalha, H., Maghalseh, M., Qutaina, J., Junaidi, K., and Rene, E. R., "Removal of Hydrogen Sulfide from Biogas Using Activated Carbon Synthes- ized from Different Locally Available Biomass wastes - a case study from Palestine," *Bioengineered*. 2020. 11(1):607–618. https://doi.org/10.1080/21655979.2020.1768736

[4] Badan Pusat Statistik Provinsi Sulawesi Barat. Luas Tanaman Perkebunan Menurut Provinsi - Tabel Statistik Badan Pusat Statistik Indonesia. .2023. [Online]. Available: https://www.bps.go.id/id/statisticstable/2/MTMxIzI=/luastanamanperkebunanmenurut- provinsi.html. (Accessed: Jul. 16, 2023).

[5] Murtius, W. S., Argo, B. D., Nurika, I., and Sukardi, S., "Identification of Availability and Lignocellulosic Properties in Coconut Dregs Waste. *Journal of Applied Agricultural Science and Technology.* 2024. 8(1): 92–105, https://doi.org/10.55043/jaast.v8i1.248

[6] Basha, N. A., Rathinavel, T., and Sridharan, H., "Activated Carbon from Coconut Shell: Synthesis and Its Commercial Applications

- A Recent Review. *Applied Science and Engineering Progress*. 2023. 16(2): 1–19. https://doi.org/10.14416/j.asep.2022.07.001

[7] Prawiranti, Y., Mandasari, W., Shofiyah, S. S., Febrianty, I. R., and Utami, N. T., "Pembuatan Karbon Aktif Ampas Kelapa dengan Aktivator Asam Fosfat (H_3PO_4) untuk Mengadsorpsi Ion Logam Besi (Fe)," *Akta Kimia Indonesia*.2024. 9(2):133. https://doi.org/10.12962/j25493736.v9i2.22084

[8] Saadi, W., Ruiz, B., Najar-Souissi, S., Ouederni, A., and Fuente, E., "High-Pressure Gas Adsorption on Activated Carbons from Pomegranate Peels Biochar: A Promising Approach for Biogas Purification," *Biomass and Bioenergy*. 2024. 186(107258):1–10. https://doi.org/10.1016/j.biombioe.2024.107258

[9] Pinchaipat, R., Koedthong, P., Boonpian, P., Vitidsant, T., and Owkusumsirisakul, J., "Chemical and electrical properties of activated carbon from Samui Island young coconut waste," *Journal of Physics: Conference Series*. 2023. 2653(1), https://doi.org/10.1088/1742-6596/2653/1/012069

[10] Masthura, Jumiati, E., and Daulay, A. H., "Effects of Activation Temperature on Characteristics and Microstructure of Coconut Shell-Based Activated Carbon," *Eurasian Journal of Analytical Chemistry*. 2018. 13(4): 384–390.

[11] Mian, I., Rehman, N., Li, X., Ullah, H., Khan, A., Choi, C., and Han, C., "Effect of Heating Rate on the Pyrolysis Behavior and Kinetics of Coconut Residue and Activated Carbon: A Comparative Study," *Energies*. 2024. 17(18):1–11, https://doi.org/10.3390/en17184605

[12] Madojemu, G. O., Eze, C. B., and Okieimen, F. E., "Optimization of Surface Area of Activated Carbons Prepared From Coconut Shells By Response Surface Methodology, *Journal of Chemical Society of Nigeria*. 2020. 45(2):354–364, 2020

[13] Purba, E., and Safitri, F., "Characteristics of Banana Stem Adsorbent (Musa Paradisiaca) For Biogas Purification With Variation of Adsorption Contact Time," *Jurnal Bahan Alam Terbarukan*. 2023. 12(1):25–31. https://doi.org/10.15294/jbat.v12i1.39600

[14] Budihardjo, M. A., Syafrudin, Samadikun, B. P., Wardhana, I. W., Ramadan, B. S., and Humaira, N. G., "Purification of Biogas from Tofu Waste Using Zeolite and Activated Carbon (AC) as Adsorbent," *Global Nest Journal*. 2021. 23(4): 491–496, https://doi.org/10.30955/gnj.003906

[15] Chen, H., Liu, L. C., Dong, S., Zhang, Y., and He, P., "Development of a New Type of Phosphoric Acid Based Geopolymer/Activated Carbon Composite for Selective CO_2 Capture," *Materials Letters*. 2022. 325: 132869. https://doi.org/10.1016/j.matlet.2022.132869.

[16] Susanti, D., Nurdiansah, H., Pramata, A. D., Rohmanuddin, T. N., Fajarin, R., Rakhmawati, Y. W., Kusuma, G. E., and Bahfie, F., "Utilization of Biomass Wastes: Coconut and Pangium edule Shells as Activated Carbon for Energy Storage Device Material. E*3S Web of Conferences*, 2023. 467(04001):1–6. https://doi.org/10.1051/e3sconf/202346704001

[17] Racero-Galaraga, D., Rhenals-Julio, J. D., Sofan-German, S., Mendoza, J. M., and Bula-Silvera, A., "Proximate Analysis in Biomass: Standards, Applications and Key Characteristics," *Results in Chemistry*. 2024. 12:101886,https://doi.org/10.1016/j.rechem.2024.101886

[18] Mohammaad, A. H., and Kijevčanin, M., "Synthesis of Activated Carbons from Water Hyacinth Biomass and Its Application as Adsorbents in Water Pollution Control," *Journal of the Serbian Chemical Society*. 2022.88(1): 69–82. https://doi.org/10.2298/JSC212121006M

[19] Yahya, M. A., Ngah, C. W. Z. C. W., Hashim, M. A., and Al-Qodah, Z., "Preparation of Activated Carbon from Desiccated Coconut Residue by Chemical Activation with NaOH. *Journal of Materials Science Research*. 2015. 5(1): 24, http://dx.doi.org/10.5539/jmsr.v5n1p24

[20] da Silva, J. C. G., Alves, J. L. F., Galdino, W. V.

de A., de Sena, R. F., and Andersen, S. L. F., "Pyrolysis Kinetics and Physicochemical Characteristics of Skin, Husk, and Shell from Green Coconut Wastes," *Energy, Ecology and Environment*. 2019. 4(3): 125–132, https://doi.org/10.1007/s40974-019-00120-x

[21] Pawar, A., Panwar, N. L., Jain, S., Jain, N. K., and Gupta, T., "Thermal Degradation of Coconut Husk Waste Biomass under Non-isothermal Condition," *Biomass Conversion and Biorefinery*. 2023. 13: 7613–7622, https://doi.org/10.1007/s13399-021-01657-w

[22] Fatmawati, A., Nurtono, T., and Widjaja, A., "Thermogravimetric kinetic-based computation of raw and pretreated coconut husk powder lignocellulosic composition. *Bioresource Technology Reports*. 2023. 22: 101500, https://doi.org/10.1016/j.biteb.2023.101500

[23] Anuwar, N. A., and Khamaruddin, P. F. M., "Optimization of Chemical Activation Conditions for Activated Carbon From Coconut Shell Using Response Surface Methodology (RSM) and Its Ability to Adsorb CO_2. *Proceedings of the Third International Conference on Separation Technology 2020 (ICoST 2020*). 2020. 234–248, https://doi.org/10.2991/aer.k.201229.032

[24] Ismail, B. P., "Ash Content Determination," in Food Analysis Laboratory Manual, Food Science Text Series. 2017:17–119. https://doi.org/10.1007/978-3-319-44127-6_11

[25] Kim, S., Lee, S. E., Baek, S. H., Choi, U., and Bae, H. J., "Preparation of Activated Carbon from Korean Anthracite: Simultaneous Control of Ash Reduction and Pore Development," *Processes*, 2023. 11:1–14. https://doi.org/10.3390/pr11102877

[26] Kong, Z., Zhang, H., Zhou, T., Xie, L., Wang, B., and Jiang, X., "Preparation, Functionalization, and Applications in Adsorption and Catalytic Separation of Carbon Dioxide and Other Atmospheric Pollutants," Separation and Purification Technology. 2025. 354, 129099. https://doi.org/10.1016/j.seppur.2024.129099

[27] Zhang, L., Tu, L.-y., Liang, Y., Chen, Q., Li, Z.-s., Li, C.-h., Wang, Z.-h., and Li, W., "Coconut-based activated carbon fibers for efficient adsorption of various organic dyes," *RSC Advances*. 2018. 8(74): 42280–42291, https://doi.org/10.1039/C8RA08990F

[28] Bakti, A. I., Gareso, P. L., and Rauf, N. Characterization of Active Carbon from Coconut Shell using X-Ray Diffraction (X-RD) and SEM-EDX Techniques. *Jurnal Penelitian Fisika dan Aplikasinya*. 2018. 8(2):115. https://doi.org/10.26740/jpfa.v8n2.p115-122

[29] Anggita, S. R., Prahesti, A. Y. P., Azizah, T. S., and Arsini, "Morphological, Crystallinity, and Functional Group Analysis of Coconut Shell-Based Activated Carbon with Carbonization Temperature Variations for Supercapacitor Electrode Potential," *Journal of Physics and Its Applications*. 2025. 7(3):59–64, https://doi.org/10.14710/jpa.v7i3.25118

[30] Sujiono, E. H., Zabrian, D., Zurnansyah, Mulyati, Zharvan, V., Samnur, and Humairah,N.A.. Fabrication and Characterization of Coconut Shell Activated Carbon using Variation Chemical Activation for Wastewater Treatment Application," *Results in Chemistry*. 2022. 4. 100291, https://doi.org/10.1016/j.rechem.2022.100291

[31] Suprianti, Y., Pangestu, Y. R., and Iriani, P., "Pengaruh Variasi Bentuk Adsorben Karbon Aktif dan Scale-up Kolom Terhadap Kinerja Adsorpsi CO2 Dalam Biogas. *Jurnal Energi dan Manufaktur*. 2023. 15(1): 26-31, https://doi.org/10.24843/JEM.2022.v015.i01.p04

[32] Pratiwi, V. D., Kamal, N., and Juhanda, S., "Analisis Pengaruh Waktu Aktivasi dan Adsorpsi dalam Pemanfaatan Karbon Aktif dari Serutan Kayu menjadi Adsorben Limbah Cair. *Jurnal Rekayasa Hijau*. 2019. 3(1):71–78, https://doi.org/10.26760/jrh.v3i1.2822

[33] Zulkefli, N. N., Masdar, M. S., Wan Isahak, W. N. R., Jahim, J. M., Md Rejab, S. A., and Lye, C. C., "Removal of Hydrogen Sulfide

From a Biogas Mimic By Using Impregnated Activated Carbon Adsorbent," *PLOS One*. 2019. 14(2): 1–25, https://doi.org/10.1371/journal.pone.0211713

[34] Tuerhong, T., and Kuerban, Z., "Preparation and characterization of cattle manure-based activated carbon for hydrogen sulfide removal at room temperature. *Journal of Environmental Chemical Engineering*. 2022. 10(2): 107177, https://doi.org/10.1016/j.jece.2022.107177

[35] Suprianti, Y., "Pemurnian Biogas untuk meningkatkan Nilai Kalor melalui Adsorpsi Dua Tahap Susunan Seri dengan Media Karbon Aktif," ELKOMIKA: *Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*. 2016. 4(2): 185–196. https://doi.org/10.26760/elkomika.v4i2.185