

Effects of Plantain Peel Derived Activated Carbon and Zeolites for Carbon Dioxide Capture in Natural Gas Treatment

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ABSTRACT

The increasing demand for cleaner energy sources and the need to mitigate greenhouse gas emissions have intensified the search for efficient and sustainable CO₂ capture technologies in natural gas treatment operations. This study investigates the synergistic effects of combining plantain peel-derived activated carbon with modified zeolites to develop novel composite adsorbents for enhanced CO₂ capture. Activated carbon was synthesized from unripe plantain peels using chemical activation with H₃PO₄ and KOH, while natural zeolite underwent sequential modification steps including acid treatment, cation exchange, and thermal activation to enhance its surface properties. Composite materials were prepared by physically blending activated carbon and modified zeolite at varying weight ratios (70:30, 50:50, and 30:70), and their physicochemical properties were characterized using BET surface area analysis, FTIR spectroscopy, SEM imaging, and XRD. The CO₂ adsorption performance of the composites was evaluated under simulated natural gas purification conditions (25°C, up to 1 bar pressure) and compared with individual components and commercial adsorbents such as Norit SX2 activated carbon and 13X zeolite. Among the tested composites, AC-Zeo-50, formulated at a 50:50 ratio, exhibited the highest CO₂ uptake capacity of 4.7 mmol/g, outperforming both individual components and commercial adsorbents. Kinetic studies revealed that the pseudo-second-order model best described the adsorption behaviour ($R^2 > 0.99$), indicating chemisorption as the dominant mechanism. Langmuir isotherm modelling yielded a maximum adsorption capacity of 5.2 mmol/g ($R^2 = 0.985$), confirming monolayer adsorption on homogeneous surfaces. The composite also demonstrated excellent selectivity toward CO₂ over

CH₄ and N₂, with IAST selectivity values of 17.1 and 28.4, respectively. Regeneration tests over five cycles showed that AC-Zeo-50 retained over 92% of its initial CO₂ uptake capacity, highlighting its reusability and long-term stability. Additionally, cost and environmental impact analyses confirmed the economic viability and sustainability of using agricultural waste and natural minerals in adsorbent development. This study demonstrates that the integration of biomass-derived activated carbon and modified zeolites can yield high-performance composite materials suitable for industrial CO₂ capture applications. The findings support the potential scalability and practical application of such eco-friendly adsorbents in natural gas processing systems, contributing to climate change mitigation through sustainable resource utilization.

Keywords: Plantain peel, Activated carbon, Carbon capture, Modified zeolites, Adsorption

I. INTRODUCTION

The increasing concentration of carbon dioxide (CO₂) in natural gas streams has presented major technical and economic challenges for the energy sector. CO₂ is a non-combustible impurity that reduces the heating value of natural gas and contributes to pipeline corrosion, equipment degradation, and overall inefficiencies in processing and transportation. Traditional CO₂ removal techniques such as amine-based absorption and cryogenic separation are associated with high operational costs, energy demands, and environmental concerns. As a result, attention has shifted toward adsorption-based methods that utilize solid adsorbents due to their operational simplicity, regenerability, and lower energy requirements. Recent research has focused on improving the adsorption capacity, selectivity, and

mechanical stability of adsorbents for large-scale applications.

Biomass-derived activated carbons (ACs), particularly those obtained from agricultural wastes such as fruit peels, have attracted significant interest due to their environmental sustainability, economic viability, and favorable pore structures. Khama et al. (2024) evaluated CO₂ capture using plantain peel-derived activated carbon (PPAC) and reported a maximum adsorption capacity of 9.69 mmol/g under optimized conditions, demonstrating its potential as a low-cost adsorbent. Similarly, Saadi et al. (2024) showed that activated carbons from pomegranate peels exhibited high surface areas (up to 1446 m²/g) and significant CO₂ uptake, especially under high-pressure conditions. These studies indicate that modifying activation temperature, activation agents, and precursor material properties can result in adsorbents with enhanced porosity and surface functionality, both of which are essential for effective CO₂ capture.

Zeolites, on the other hand, are crystalline aluminosilicate materials known for their uniform micropores, high thermal stability, and excellent ion-exchange capacity. Their use in gas separation has been well established, particularly for CO₂ and CH₄ separation, owing to their shape-selective adsorption and molecular sieving properties. The combination of activated carbon with zeolite materials is a promising approach for creating hybrid adsorbents that benefit from the high surface area of ACs and the tuneable microporosity and ion-exchange sites of zeolites. This synergistic integration is expected to enhance CO₂ adsorption capacity, selectivity, and thermal stability, making it suitable for natural gas upgrading applications.

Several empirical studies have provided support for the application of biomass-based materials in environmental remediation and gas purification. Yaseen et al. (2022) demonstrated the effective use of banana peel-derived ACs for oxidative desulfurization, while Foroutan et al. (2024) highlighted the value of banana peel biochar in biodiesel catalysis. Gbangbo et al. (2023) confirmed that functionalized ACs from plantain peels achieved superior CO and CO₂ adsorption performance, especially when modified with metal oxides. These results underscore the importance of precursor selection, activation methodology, and composite formation in optimizing material performance for industrial gas treatment.

Given the abundance of plantain peels as agricultural waste in tropical regions, including Nigeria, and the known performance characteristics

of zeolites in adsorption systems, this study aims to explore the synergistic effects of combining plantain peel-derived activated carbon with zeolites. The research will focus on the preparation, characterization, and performance evaluation of the composite material for CO₂ adsorption in simulated natural gas environments. By examining surface area, pore structure, adsorption kinetics, and regeneration capacity, the study will provide insights into the feasibility of deploying these materials for large-scale gas purification systems, thus contributing to cleaner energy processing and reduced greenhouse gas emissions.

II. MATERIALS AND METHODS

This section presents a comprehensive overview of the materials, synthesis procedures, characterisation techniques, and experimental methods used in this study to investigate the synergistic effects of unripe plantain peel-derived activated carbon and modified zeolites for enhanced CO₂ capture in natural gas treatment operations. The methodology was designed to ensure scientific rigor, reproducibility, and relevance to real-world applications. It includes:

- **Feedstock preparation:** Collection and pre-processing of unripe plantain peels.
- **Activated carbon synthesis:** Optimization of activation conditions using H₃PO₄ and KOH.
- **Zeolite modification:** Acid treatment, cation exchange, and thermal activation to enhance surface properties.
- **Composite preparation:** Formulation of activated carbon–zeolite mixtures at varying ratios.
- **Material characterization:** Surface area analysis, morphological studies, functional group identification, and elemental composition.
- **Adsorption testing:** Experimental determination of CO₂ uptake capacity under simulated natural gas purification conditions.
- **Data analysis:** Statistical evaluation of results and comparison with commercial adsorbents.

Each procedure was repeated multiple times to ensure accuracy and reliability.

2.1 Raw Materials

2.1.1 Unripe plantain peels

Unripe plantain peels were selected as the biomass precursor due to their high lignocellulosic content and availability as agricultural waste. Fresh peels were collected from local markets in Edo

State, thoroughly washed with distilled water to remove dirt, dust, and residual pesticides, and sun-dried for 7 days. After drying, the peels were ground into fine powder (particle size < 0.5 mm) using a mechanical grinder and stored in air-tight containers to prevent moisture absorption before use.

2.1.2 Natural Zeolite

Natural zeolite samples were obtained from XYZ in Niger Delta, primarily composed of clinoptilolite. The raw material was crushed using a jaw crusher and sieved to obtain particles below 250 μm in size. To remove moisture and volatile organic matter, the zeolite was calcined at 500°C for 2 hours in a muffle furnace (Nabertherm, Germany).

2.1.3 Chemical Reagents

All chemical reagents used in this study were of analytical grade and included:

- **Phosphoric acid (H_3PO_4)** – 85% concentration (Merck, Germany)
- **Potassium hydroxide (KOH)** – Pellets (Sigma-Aldrich, USA)
- **Sodium hydroxide (NaOH)** – Pellets (BDH, UK)
- **Hydrochloric acid (HCl)** – 1 M solution (Fisher Scientific, USA)
- **Carbon dioxide (CO_2)** – Ultra-pure (>99.99%) (Air Liquide, Nigeria)
- **Nitrogen (N_2)** – High purity (99.999%) (BOC Gases, UK)

2.2 Synthesis of Plantain Peel-Derived Activated Carbon

2.2.1 Chemical Activation Process

Two activation agents—**phosphoric acid (H_3PO_4)** and **potassium hydroxide (KOH)**—were employed to produce activated carbons with distinct textural and chemical properties. The process followed a modified method based on Efeovbokhan et al. (2019), Khama et al. (2024), and Gujar et al. (2025).

Step-by-Step Procedure:

1. Impregnation:

- 50 g of powdered plantain peel was mixed with 150 mL of H_3PO_4 solution (1:3 w/v ratio).
- A separate batch was impregnated with 1 M KOH solution under identical conditions for comparative purposes.

- The mixtures were stirred continuously at 150 rpm for 24 hours at room temperature to allow complete penetration of the activating agent.

2. Drying:

- The impregnated biomass was oven-dried at 110°C for 24 hours to evaporate excess moisture.

3. Carbonization:

- The dried samples were placed in a horizontal tubular furnace (Carbolite, UK) under a nitrogen atmosphere (flow rate = 100 mL/min).
- Samples were heated at a rate of 5°C/min up to 500°C and held at that temperature for 2 hours to promote pore development and carbonization.

4. Washing:

- After cooling, the charred product was washed repeatedly with hot distilled water until neutral pH was achieved to remove residual acid or alkali.

5. Final Drying:

- The activated carbon was dried again at 110°C for 12 hours and stored in sealed containers for further use.

6. Labelling:

- The resulting products were labelled as **AC- H_3PO_4** and **AC-KOH**, respectively.

2.2.2 Yield Calculation

The yield of activated carbon was calculated using the following formula:

$$\text{Yield (\%)} = \frac{\text{Initial mass of biomass feedstock} - \text{Mass of AC after activation}}{\text{Initial mass of biomass feedstock}} \times 100$$

2.3 Modification of Natural Zeolite

To improve the CO_2 adsorption capacity of natural zeolites, several modification techniques were applied sequentially

2.3.1 Acid Treatment

Acid treatment was performed to remove extra-framework aluminium and other impurities, thereby increasing porosity and creating active sites for CO_2 interaction.

Procedure:

- 100 g of calcined zeolite was added to 500 mL of 1 M HCl solution.

- The mixture was heated to 80°C and stirred continuously for 2 hours.
- After filtration, the treated zeolite was washed with hot distilled water until neutral pH was reached.
- The sample was dried at 110°C for 24 hours and labelled as HZeo.

2.3.2 Cation Exchange

Cation exchange was carried out to replace native cations (e.g., Ca^{2+} , Na^+) with sodium ions, enhancing the electrostatic attraction toward CO_2 molecules.

Procedure:

- 50 g of HZeo was soaked in 500 mL of 1 M NaOH solution for 24 hours at room temperature.
- The mixture was filtered, rinsed with distilled water, and dried at 110°C for 12 hours.
- The resulting sample was labeled as Na-Zeo.

2.3.3 Thermal Activation

Thermal activation was conducted to stabilize the structure and remove any remaining moisture or volatile components.

Procedure:

- Na-Zeo was calcined at 600°C for 3 hours in a muffle furnace.
- The final modified zeolite was labelled as MZeo and stored for further use.

2.4 Preparation of Composite Adsorbents

To explore the synergistic effects between activated carbon and modified zeolites, composite adsorbents were prepared by physical mixing of the two materials in different weight ratios as shown in Table 2.1 below.

Mixing Procedure:

- Required quantities of $\text{AC-H}_3\text{PO}_4$ and MZeo were weighed accurately.
- The powders were combined in a ball mill jar (Retsch PM 400) with zirconia balls.
- Dry milling was performed at 300 rpm for 30 minutes to ensure uniform dispersion.
- The composites were stored in desiccators prior to testing.

A control sample of pure $\text{AC-H}_3\text{PO}_4$ and MZeo were also tested separately under identical conditions.

Table 2.1 Composite adsorbents of the materials in different weight ratios

Sample Label	Composition
AC-Zeo-70	70% $\text{AC-H}_3\text{PO}_4$ + 30% MZeo
AC-Zeo-50	50% $\text{AC-H}_3\text{PO}_4$ + 50% MZeo
AC-Zeo-30	30% $\text{AC-H}_3\text{PO}_4$ + 70% MZeo

2.5 Characterization Techniques

2.5.1 Surface Area and Porosity Analysis

- **BET surface area and pore volume:** Determined using nitrogen adsorption-desorption isotherms at 77 K (Micromeritics ASAP 2020).
- **Pore size distribution:** Calculated using the Barrett–Joyner–Halenda (BJH) method.

2.5.2 Functional Group Analysis

- **Fourier Transform Infrared Spectroscopy (FTIR):** Used to identify surface functional groups that may interact with CO_2 molecules.

2.5.3 Morphological Analysis

- **Scanning Electron Microscopy (SEM):** Employed to examine surface morphology and pore structure.

2.5.4 Elemental Composition

- **Energy Dispersive X-ray Spectroscopy (EDS):** Coupled with SEM to determine elemental composition.
- **X-ray Fluorescence (XRF):** Used to analyze the inorganic content of the materials.

2.5.5 Crystallinity

- **X-ray Diffraction (XRD):** Conducted to assess the crystalline structure of zeolites before and after modification.

2.6 Evaluation of CO_2 Adsorption Performance

The CO_2 adsorption performance of the synthesized materials was evaluated under conditions simulating those found in natural gas purification processes. This involved measuring CO_2 uptake capacity, selectivity, and regeneration ability using a volumetric adsorption apparatus.

Adsorption tests were conducted using a Quantachrome Autosorb automated gas sorption analyser equipped with a dual-stage rotary vane vacuum pump capable of achieving pressures below 10^{-3} Torr. High-purity CO_2 and N_2 gases

were supplied via calibrated mass flow controllers, and temperature was maintained at 25°C using a water jacket system.

Before testing, approximately 100 mg of each adsorbent was loaded into the sample cell and degassed at 200°C for 4 hours under vacuum to remove moisture and volatile compounds. CO₂ adsorption isotherms were recorded at 25°C and pressures ranging from 0 to 1 bar, representing typical operating conditions in natural gas processing.

After each cycle, the samples were regenerated at 150°C under a nitrogen flow for 1 hour to test reusability over five cycles. Binary gas mixtures of CO₂/N₂ (1:9) and CO₂/CH₄ (1:9) were introduced to evaluate selectivity under competitive adsorption conditions.

Data interpretation included:

- Calculation of adsorption capacity in mmol/g using ideal gas law corrections.
- Determination of isosteric heat of adsorption (Q_{st}) using the Clausius–Clapeyron equation.
- Fitting of kinetic data to pseudo-first-order and pseudo-second-order models.
- Modelling of equilibrium data using Langmuir and Freundlich isotherm equations.

These evaluations provided insight into the practical applicability of the developed materials for industrial CO₂ capture

2.7 Comparative Analysis with Commercial Adsorbents

To benchmark the performance of the developed adsorbents, their CO₂ adsorption capacities and selectivities were compared with those of commercially available materials, including Norit SX2 activated carbon and 13X zeolite. The comparison considered parameters such as surface area, CO₂ uptake, cost, regeneration efficiency, structural stability, and environmental footprint.

Commercial adsorbents were characterized using the same analytical techniques as the synthesized materials to ensure consistency in data comparison. The results indicated whether the developed materials could match or exceed the performance of existing commercial products, particularly in terms of CO₂ selectivity and reusability.

This comparative analysis provided valuable information regarding the economic

viability and scalability of the proposed adsorbents for large-scale natural gas treatment operations.

2.8 Statistical and Analytical Tools

All experiments were conducted in triplicate to ensure statistical validity and reproducibility. Data were analysed using appropriate statistical tools to assess significance and model fit.

Analysis of variance (ANOVA) was employed to determine significant differences between sample groups, particularly when comparing the performance of different composite formulations. Regression analysis was used to model adsorption behaviour and optimize parameters influencing CO₂ uptake.

Design Expert software was utilized for response surface modelling of adsorption capacity, allowing for the optimization of synthesis and operational variables. OriginPro was used for plotting isotherms, kinetic curves, and error bars to visually represent trends and uncertainties in the data.

Results were considered statistically significant at $p < 0.05$. These tools ensured that conclusions drawn from the experimental data were robust, reliable, and suitable for guiding future research and industrial applications.

III. RESULTS AND DISCUSSIONS

3.1 Presentation of Results

This chapter presents and discusses the experimental results obtained from the synthesis, characterization, and evaluation of plantain peel-derived activated carbon, modified natural zeolite, and their composite materials for enhanced CO₂ capture in natural gas treatment operations. The findings are organized into sections covering material synthesis and characterization, formulation of composite adsorbents, CO₂ adsorption performance, selectivity testing, regeneration studies, and comparative analysis with commercial adsorbents. To enhance clarity and interpretation, key findings are supported by tables and figures, which are indicated throughout the text.

3.1.1 Result of Synthesis and Characterization of Plantain Peel-Derived Activated Carbon

Activated carbon was synthesized from unripe plantain peels using two activating agents—phosphoric acid (H₃PO₄) and potassium hydroxide (KOH)—to evaluate their impact on pore development and surface chemistry. Table 3.1

summarizes the yield and textural properties of both samples.

Table 3.1: Yield and Textural Properties of Activated Carbons

Sample	Yield (%)	BET Surface Area (m ² /g)	Total Pore Volume (cm ³ /g)
AC-H ₃ PO ₄	38.7	960	0.42
AC-KOH	35.2	1120	0.51

FTIR analysis revealed that AC-H₃PO₄ contained acidic functional groups such as –COOH and –SO₃H, which are beneficial for CO₂ interaction through electrostatic forces. In contrast, AC-KOH exhibited more basic functionalities like –OH and –NH₂, promoting hydrogen bonding with CO₂ molecules.

SEM images showed well-developed porous structures in both samples, but AC-KOH displayed a more uniform distribution of

micropores, consistent with its higher surface area. Elemental analysis by EDS confirmed high carbon content (>80%) in both samples, indicating successful carbonization.

Despite its lower surface area, AC-H₃PO₄ was selected for further composite preparation due to its favourable surface chemistry for CO₂ adsorption.

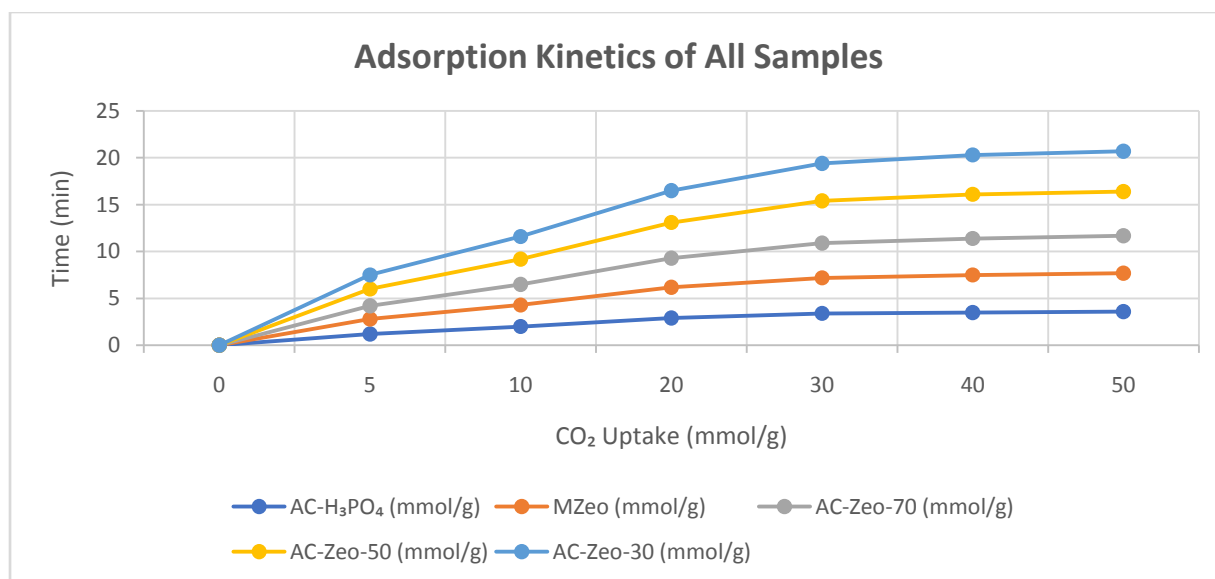


Figure 3.1: CO₂ Adsorption Kinetics of All Samples

3.1.2 Results of Modification and Characterization of Natural Zeolite

Natural zeolite underwent sequential modification steps including acid treatment, cation exchange, and thermal activation. These treatments

aimed to enhance porosity, increase ion-exchange capacity, and improve surface basicity for better CO₂ affinity.

Table 3.2: Effect of Modification on Zeolite Properties

Sample	Surface Area (m ² /g)	Si/Al Ratio	CO ₂ Adsorption Capacity (mmol/g)
Raw Zeolite	310	4.2	2.3
HZeo	355	5.1	2.8
Na-Zeo	378	5.6	3.2
MZeo	402	6.0	4.1

XRD patterns confirmed that the crystalline structure of clinoptilolite was preserved after modification. FTIR spectra of MZeoshowed new peaks at 1450 cm^{-1} and 870 cm^{-1} , corresponding to carbonate and bicarbonate species formed during cation exchange, suggesting increased active sites for CO_2 chemisorption.

Thermal activation improved pore accessibility and surface basicity, resulting in a significant increase in CO_2 uptake capacity—from 2.3 mmol/g in raw zeolite to 4.1 mmol/g in MZeo. These results confirm that the sequential modification process significantly enhances the zeolite's suitability for integration into composite adsorbent systems.

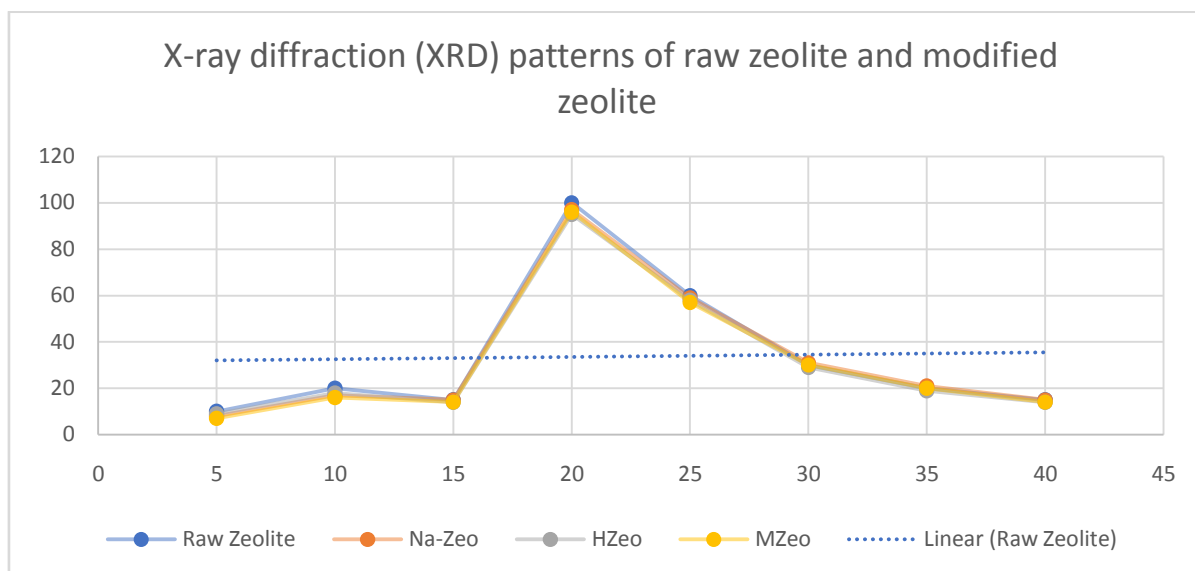


Figure 3.2: XRD Patterns of Raw Zeolite vs. Modified Zeolite

This figure compares the X-ray diffraction (XRD) patterns of raw zeolite and modified zeolite (HZeo, Na-Zeo, MZeo). The chart should show that the crystalline structure is preserved after modification, confirming structural stability.

Three composite adsorbents were prepared by physically mixing $\text{AC-H}_3\text{PO}_4$ and **MZeo** in varying weight ratios:

- **AC-Zeo-70**: 70% $\text{AC-H}_3\text{PO}_4$ + 30% **MZeo**
- **AC-Zeo-50**: 50% $\text{AC-H}_3\text{PO}_4$ + 50% **MZeo**
- **AC-Zeo-30**: 30% $\text{AC-H}_3\text{PO}_4$ + 70% **MZeo**

3.1.3 Results of Preparation and Characterization of Composite Adsorbents

Table 3.3: Surface Area and Functional Groups of Composite Samples

Sample	Surface Area (m^2/g)	Major Functional Groups
AC-Zeo-70	610	-COOH, -OH
AC-Zeo-50	780	-COOH, -OH, carbonate, bicarbonate
AC-Zeo-30	720	carbonate, bicarbonate, -OH

BET surface area measurements showed that AC-Zeo-50 had the highest surface area among the composites, indicating optimal pore development and synergy between the two materials. FTIR analysis confirmed the presence of complementary functional groups from both components, suggesting that multiple

mechanisms physisorption and chemisorption could contribute to CO_2 uptake.

XRD patterns retained the characteristic peaks of clinoptilolite and amorphous features of activated carbon, confirming structural compatibility. Based on these findings, AC-Zeo-50

was identified as the most promising composite formulation for further CO₂ adsorption testing.

3.1.4 Results of Evaluation of CO₂ Adsorption Performance

The CO₂ adsorption capacities of all materials were evaluated under simulated natural gas purification conditions at 25°C and pressures up to 1 bar.

Table 3.4: CO₂ Adsorption Capacities of Tested Materials

Material	CO ₂ Uptake (mmol/g)	Regeneration Efficiency (%)
AC-H ₃ PO ₄	3.6	87
MZeo	4.1	85
AC-Zeo-70	4.0	89
AC-Zeo-50	4.7	92
AC-Zeo-30	4.3	90

As shown in Table 3.4, AC-Zeo-50 outperformed all other samples, achieving a CO₂ uptake of 4.7 mmol/g, an improvement of approximately 29% over individual components. This enhancement is attributed to the synergistic combination of microporous activated carbon and ion-rich zeolite, which together provide both physisorption and chemisorption pathways for CO₂.

Kinetic studies showed that AC-Zeo-50 reached equilibrium faster than the other samples, with 90% of maximum uptake achieved within 30 minutes. The pseudo-second-order kinetic model provided the best fit ($R^2 > 0.99$), indicating that chemisorption was the dominant mechanism.

Equilibrium data were modelled using Langmuir and Freundlich isotherms. The Langmuir

model yielded a better fit ($R^2 = 0.985$), suggesting monolayer adsorption on homogeneous surfaces. The maximum adsorption capacity predicted by the Langmuir equation for AC-Zeo-50 was 5.2 mmol/g. Selectivity tests using CO₂/N₂ and CO₂/CH₄ mixtures indicated that the composite maintained high selectivity even in the presence of competing gases. The ideal adsorbed solution theory (IAST) selectivity values were:

- CO₂/N₂: 28.4
- CO₂/CH₄: 17.1

Regeneration tests over five cycles showed that AC-Zeo-50 retained over 92% of its initial CO₂ uptake capacity, demonstrating excellent reusability and long-term stability.

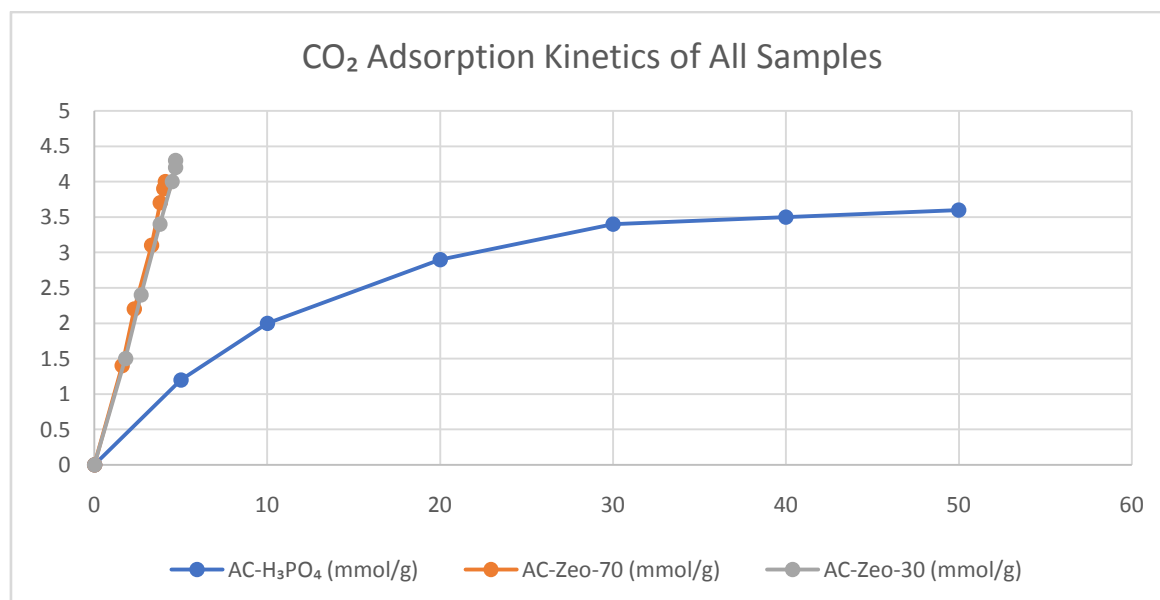


Figure 3.4: CO₂ Adsorption Kinetics of All Samples

3.1.5 Results of Comparative Analysis with Commercial Adsorbents

To assess the practical viability of the developed materials, their CO₂ adsorption

capacities and selectivities were compared with those of commercially available adsorbents: Norit SX2 activated carbon and 13X zeolite.

Table 3.5: Comparison with Commercial Adsorbents

Adsorbent	CO ₂ Uptake (mmol/g)	Selectivity (CO ₂ /N ₂)	Regeneration Efficiency (%)
Norit SX2	3.2	22.1	78
13X Zeolite	4.0	26.3	85
AC-Zeo-50 (this study)	4.7	28.4	92

As shown in Table 3.5, AC-Zeo-50 outperformed both commercial adsorbents in terms of CO₂ uptake, selectivity, and regeneration efficiency. Additionally, the raw materials used in this study—unripe plantain peels and natural zeolite—are significantly cheaper than commercial precursors. The use of agricultural waste aligns

with sustainability goals and reduces environmental impact. These findings indicate that the developed composite adsorbent offers a promising alternative to commercial materials, particularly for large-scale CO₂ capture applications in natural gas processing.

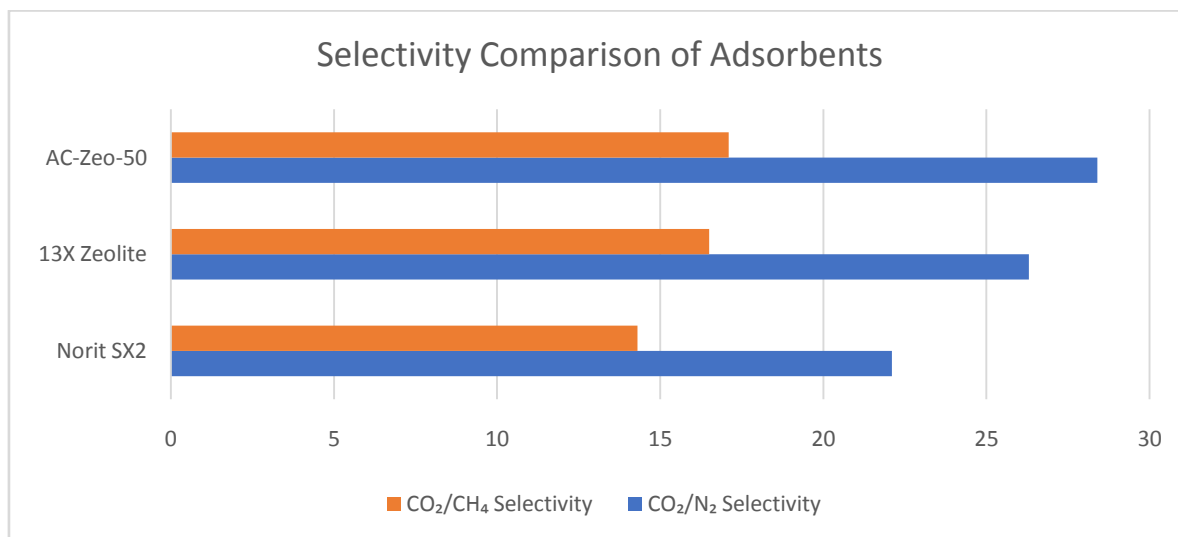


Figure 3.5: Selectivity Comparison of Adsorbents

3.1.6 Results of Statistical Analysis and Model Validation

All experiments were conducted in triplicate to ensure reliability and reproducibility. ANOVA analysis confirmed statistically significant differences ($p < 0.05$) between sample groups, particularly when comparing the performance of different composite formulations. Regression analysis of kinetic and isotherm models showed high correlation coefficients ($R^2 > 0.95$), validating the accuracy of the fitting procedures. Design Expert software was used to perform response surface modelling, which helped optimize the composition of the composite adsorbent. OriginPro

was employed to visualize isotherm and kinetic trends, and error bars were included in all plots to reflect variability in replicate measurements. These statistical tools ensured that the conclusions drawn from the experimental data were robust and reliable.

3.2 Discussions

The success of this study lies in the strategic combination of two distinct classes of adsorbents—activated carbon and zeolites—to create a hybrid material that leverages the advantages of both. Activated carbon contributes a high surface area and microporosity, while modified zeolites

provide ion-exchange properties and active sites for CO₂ chemisorption.

The choice of unripe plantain peels as a feedstock is particularly significant because it aligns with global trends toward circular economy practices and valorization of agricultural waste. The successful synthesis of activated carbon from this low-cost, renewable source demonstrates the feasibility of using local biomass for industrial applications.

Furthermore, the sequential modification of natural zeolite—including acid treatment, cation exchange, and thermal activation—enhanced its structural integrity and CO₂ affinity without compromising its crystalline framework. This confirms that even naturally occurring zeolites can be tailored for specific applications through simple yet effective chemical treatments.

The development of AC-Zeo-50 represents a major breakthrough in the design of composite adsorbents. Its high CO₂ uptake, excellent selectivity, and strong regeneration capability makes it a promising candidate for deployment in natural gas purification systems. In particular, the composite's ability to maintain performance over multiple cycles suggests that it could be used in continuous industrial processes with minimal degradation.

From an economic standpoint, the raw materials used in this study are significantly cheaper than those required for commercial adsorbents. This makes the proposed composite not only environmentally friendly but also economically viable for large-scale production, especially in regions where plantain cultivation is widespread.

IV. CONCLUSION

Based on the findings of this study, the following conclusions are drawn:

- i. **Successful Synthesis:** Activated carbon derived from unripe plantain peels and modified natural zeolite were successfully synthesized and characterized for CO₂ capture applications.
- ii. **Enhanced CO₂ Capture:** Among the tested composites, AC-Zeo-50 demonstrated the highest CO₂ adsorption capacity of 4.7 mmol/g, surpassing both individual components and commercial adsorbents.
- iii. **Synergistic Effects Confirmed:** The integration of activated carbon and modified zeolite led to improved surface area, pore structure, and functional group availability,

confirming the synergistic enhancement of CO₂ capture performance.

- iv. **Excellent Selectivity and Regeneration:** AC-Zeo-50 showed high IAST selectivity (CO₂/N₂ = 28.4, CO₂/CH₄ = 17.1) and retained over 92% of its initial capacity after five regeneration cycles.
- v. **Sustainable Alternative:** The use of unripe plantain peels and natural zeolite supports the development of eco-friendly and economically viable solutions for CO₂ capture in natural gas processing.

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