ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

# Effect of Moisture Content on $CO_2$ Adsorption Efficiency of Biomass-Derived Activated Carbon

*Nwafor, Nyimeochen Chu[1]; Akankali Chukwuyemike Emmanuel[2]
Efetobor, Mudiaga Gideon[2]; Oritsebinone, Esther Imoh[2]
Nwandieze, Fortune Onyedikachi[3]

[1]Department of Petroleum and Gas Engineering, Faculty of Engineering, University of Port Harcourt, Nigeria

[2]Department of Chemical/Petroleum Technology, SSLT, Univeristy of Port Harcourt

Department of Physics with Electronics, SSLT, University of Port Harcourt

***Corresponding Author**

## Abstract

The activated carbons were conditioned to Carbon dioxide ($CO_2$) emissions from industrial activities continue to accelerate global warming, necessitating the development of efficient and sustainable post-combustion carbon capture technologies.

Activated carbon produced from agricultural waste has emerged as a promising low-cost adsorbent for $CO_2$ capture; however, the influence of moisture on its adsorption performance remains insufficiently understood. This study investigated the effect of moisture content on the $CO_2$ adsorption capacity of activated carbon derived from palm kernel shell (PKS), coconut shell (CS), and groundnut shell (GS). The biomass precursors were carbonized at optimized temperatures of 750°C, 600°C, and 450°C, respectively, and chemically activated using potassium hydroxide (KOH).

moisture contents of 0%, 5%, and 10% before $CO_2$ adsorption experiments were conducted at temperatures of 30°C, 40°C, and 50°C under pressures of 10, 15, and 20 psi using a locally fabricated flow-loop apparatus based on Sieverts' law. The adsorbents were characterized using Brunauer–Emmett–Teller (BET) surface area analysis, Fourier Transform Infrared (FTIR) spectroscopy, and Scanning Electron Microscopy coupled with Energy Dispersive X-ray spectroscopy (SEM-EDX). The results showed that moisture significantly enhanced the $CO_2$ adsorption performance of all adsorbents. Palm kernel shell exhibited the highest adsorption capacity of 2.640 mmol $g^{-1}$ at 10% moisture, 50°C, and 20 psi, followed by coconut shell (2.298 mmol $g^{-1}$) and groundnut shell (1.300 mmol $g^{-1}$). Increasing the moisture content from 0% to 10% improved adsorption capacities by 240%,

189%, and 194% for PKS, CS, and GS, respectively. BET analysis further demonstrated that moisture conditioning increased the surface area and pore volume of PKS from 237.018 to 736.79 $m^2$ $g^{-1}$ and from1.177 to 2.853 $cm^3$ $g^{-1}$, respectively, while FTIR analysis confirmed the formation of oxygen-containing functional groups and aromatic carbon structures that enhanced $CO_2$ adsorption. These findings demonstrate that moderate moisture levels (5-10%) substantially improve the adsorption performance of biomass-derived activated carbons by increasing pore accessibility and providing additional active adsorption sites through water-$CO_2$ interactions. Among the investigated adsorbents, palm kernel shell showed the greatest potential as an efficient and sustainable material for post-combustion $CO_2$ capture in humid flue gas environments.

**Keywords;-** Carbon dioxide capture; Activated carbon; Agricultural biomass; Palm kernel shell; Coconut shell; Groundnut shell; Moisture effect; Post-combustion capture; Adsorption; Carbon capture and storage (CCS); KOH activation.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

## Introduction

The continuous rise in atmospheric $CO_2$ concentrations, primarily from fossil-fuel combustion, has intensified global warming and its environmental consequences (Pachauri & Reisinger, 2007; Metz et al., 2005). Fossil-fuel-fired power plants are the largest point sources, necessitating urgent mitigation through post-combustion capture technologies (IPCC, 2007). Among various approaches, adsorption using solid porous materials offers advantages such as low energy consumption, easy regeneration, and operational flexibility (Siriwardane et al., 2001; Zhao et al., 2017). Activated carbon (AC) has attracted considerable attention due to its high surface area, tunable porosity, thermal stability, and low cost, especially when derived from agricultural waste (Nyamful et al., 2021; Mustapha et al., 2021). However, industrial flue gases typically contain water vapour (5–15%), which can significantly affect adsorption performance. The influence of moisture on $CO_2$ uptake is complex: while high humidity may block micropores and reduce capacity (Zhang et al., 2022; Chiang et al., 2017), moderate moisture can enhance adsorption through hydration interactions, formation of water bridges, and interaction with chemical activators such as KOH (Xiao et al., 2015; Saeidi Harzand, 2018). Ozdemir and Schroeder (2009) reported that moisture affects adsorption isotherms and surface properties of coals, while Yoro et al. (2019) observed increased $CO_2$ uptake on polyaspartamide in the presence of water. Nevertheless, systematic studies on the effect of controlled moisture levels on biomass-derived ACs remain scarce, especially for tropical agricultural wastes like palm kernel shell, coconut shell, and groundnut shell.

This study aims to fill this gap by (i) preparing AC from PKS, CS, and GS via carbonization and KOH activation, (ii) conditioning the adsorbents to 0%, 5%, and 10% moisture, (iii) evaluating $CO_2$ adsorption at varying temperatures (30–50°C) and pressures (10–20 psi), and (iv) elucidating the mechanisms through BET, FTIR, and SEM-EDX characterization.

## Materials and Methods

### 2.1 Preparation of Activated Carbon

Palm kernel shell, coconut shell, and groundnut shell were collected from Choba Market, Rivers State, Nigeria. Samples were washed, dried at 80°C, crushed, and sieved to
0.5 mm. Carbonization was performed in a muffle furnace: PKS at 750°C for 3 h, CS at 600°C for 3 h, and GS at 300°C for 1 h (Chuan & Hing, 2017; Zhao et al., 2020). The resulting chars were activated with 1 M KOH at room temperature for 48 h with regular agitation, then rinsed with distilled water until pH 6–7, dried at 120°C, and stored in airtight containers.

### 2.2 Moisture Conditioning

Moisture levels of 0%, 5%, and 10% were established by adding distilled water (100 mL per 500 g of AC) and drying at 90°C with periodic weighing until target moisture was achieved (Helmi, 2013). Moisture percentage was calculated as:
% moisture = (Initial weight – Final weight)
/ Initial weight × 100%.
Samples were stored in sealed bottles to maintain fixed moisture.

### 2.3 $CO_2$ Adsorption Experiment

A locally fabricated flow-loop apparatus based on Sieverts' law (Jackson et al., 2009) was used. The system comprised a $CO_2$ cylinder, staging manifold (8 in length, 2⅛ in diameter), reactor (13 in length, ¼ in diameter), digital water bath, vacuum pump, and pressure gauges. About 0.15 g of AC was loaded into the reactor, immersed in a water bath at target temperature (30, 40, or 50°C), and equilibrated for 30 min. After evacuating air, $CO_2$ was introduced into the staging manifold to pressures of 10, 15, and 20 psi, then dosed into the reactor. Adsorption proceeded for 45 min (optimum contact time determined from preliminary tests). Pressure drop ($P_1 – P_2$) was recorded, and adsorption capacity (mmol/g) was calculated volumetrically using the ideal gas law, accounting for volumes of the manifold, reactor, and pipe fittings. Cumulative capacity was the sum of capacities at each pressure step.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

## 2.4 Characterization

BET surface area and pore properties were measured with a Micromeritics TriStar 3000 V4.02 at 77 K using $N_2$, after degassing at 473 K for 3 h. FTIR spectra (4000–400 $cm^{-1}$) were obtained with a Bruker Vertex 80v spectrometer using KBr pellets (500 scans, 4 $cm^{-1}$ resolution). SEM-EDX was performed on a Quanta 250 microscope equipped with EDX. All analyses were conducted on both dry and wet (10% moisture) PKS samples to highlight structural changes.

## Results and Discussion

## 3.1 Effect of Moisture on $CO_2$ Adsorption

**Table 1: Cumulative $CO_2$ Adsorption Capacity of Coconut Shell (CS)Groundnut Shell (GS)**

The $CO_2$ adsorption capacities for coconut shell (CS), groundnut shell (GS), and palm kernel shell (PKS) activated carbons at varying moisture contents, temperatures, and pressures are presented in Tables 1–3. Adsorption experiments were conducted at 30°C, 40°C, and 50°C under 10, 15, and 20 psi, with a retention time of 45 minutes. Cumulative capacities (sum of capacities at 10, 15, and 20 psi) are reported.

### Coconut Shell (CS)

Table 1 presents the cumulative adsorption capacities for CS. At 30°C, adsorption increased progressively with moisture: 0.660 mmol/g (0%), 0.970 mmol/g (5%), and 1.060 mmol/g (10%). At 40°C, the values rose to 0.760 mmol/g (0%), 1.420 mmol/g (5%), and 1.720 mmol/g (10%). At 50°C, capacities reached 1.212 mmol/g (0%), 1.964 mmol/g (5%), and 2.298 mmol/g (10%)– an 89.6% improvement from dry to 10% moisture. Figure 1 (See Figure 4.3 in the original dissertation) illustrates the adsorption trend at 50°C, showing the clear moisture enhancement effect.

| Temperature (°C) | 0% Moisture (mmol/g) | 5% Moisture (mmol/g) | 10% Moisture (mmol/g) |
|---|---|---|---|
| 30 | 0.660 | 0.970 | 1.060 |
| 40 | 0.760 | 1.420 | 1.720 |
| 50 | 1.212 | 1.964 | 2.298 |

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

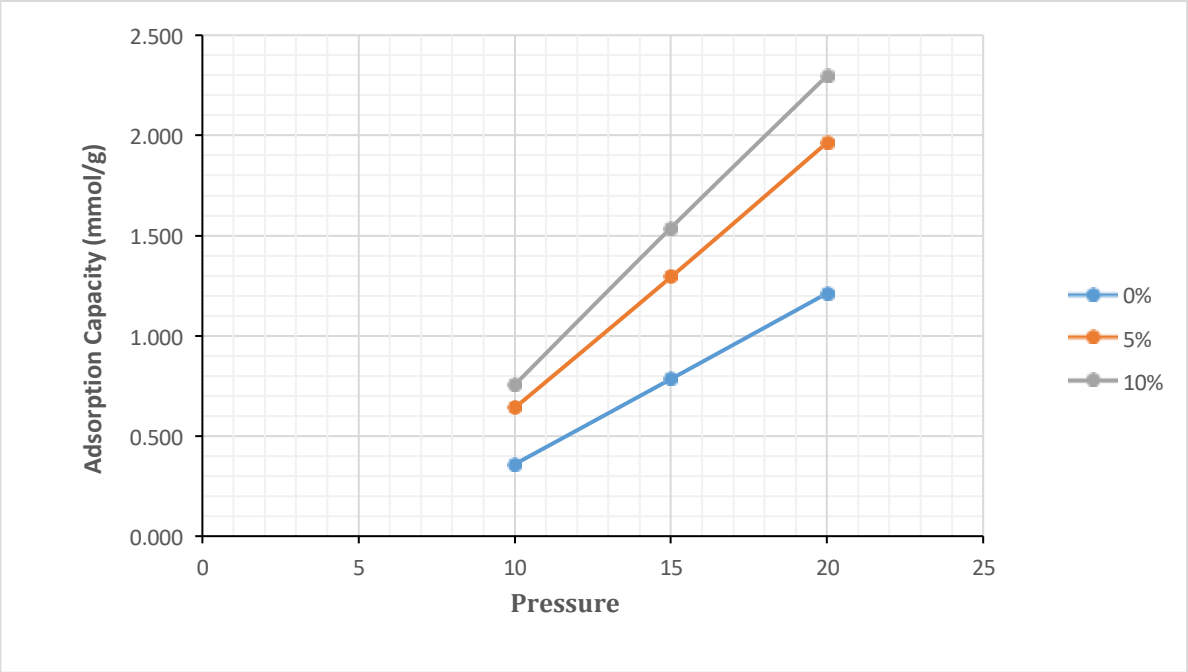



**Figure 1: Adsorption capacity for $CO_2$ of Coconut (CS) at 50°C**

**Groundnut Shell (GS)**

Table 2 presents the cumulative adsorption capacities for GS. At 30°C, adsorption decreased slightly with moisture: 0.620 mmol/g (0%), 0.568 mmol/g (5%), and 0.557 mmol/g (10%). This initial decline is attributed to pore blocking at low temperatures. However, at 40°C, the trend reversed: 0.580 mmol/g (0%), 0.630 mmol/g(5%), and 0.960 mmol/g (10%). At 50°C, adsorption rose from 0.669 mmol/g (dry) to1.300 mmol/g (10% moisture) – a 94.3% enhancement.

Figure 2 (See Figure 4.6) illustrates this trend, showing that higher temperatures overcome diffusion limitations and allow moisture-enhanced adsorption to dominate.

**Table 2: Cumulative $CO_2$ Adsorption Capacity of Groundnut Shell (GS)**

| Temperature (°C) | 0% Moisture (mmol/g) | 5% Moisture (mmol/g) | 10% Moisture (mmol/g) |
|---|---|---|---|
| 30 | 0.620 | 0.568 | 0.557 |
| 40 | 0.580 | 0.630 | 0.960 |
| 50 | 0.669 | 1.220 | 1.300 |

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

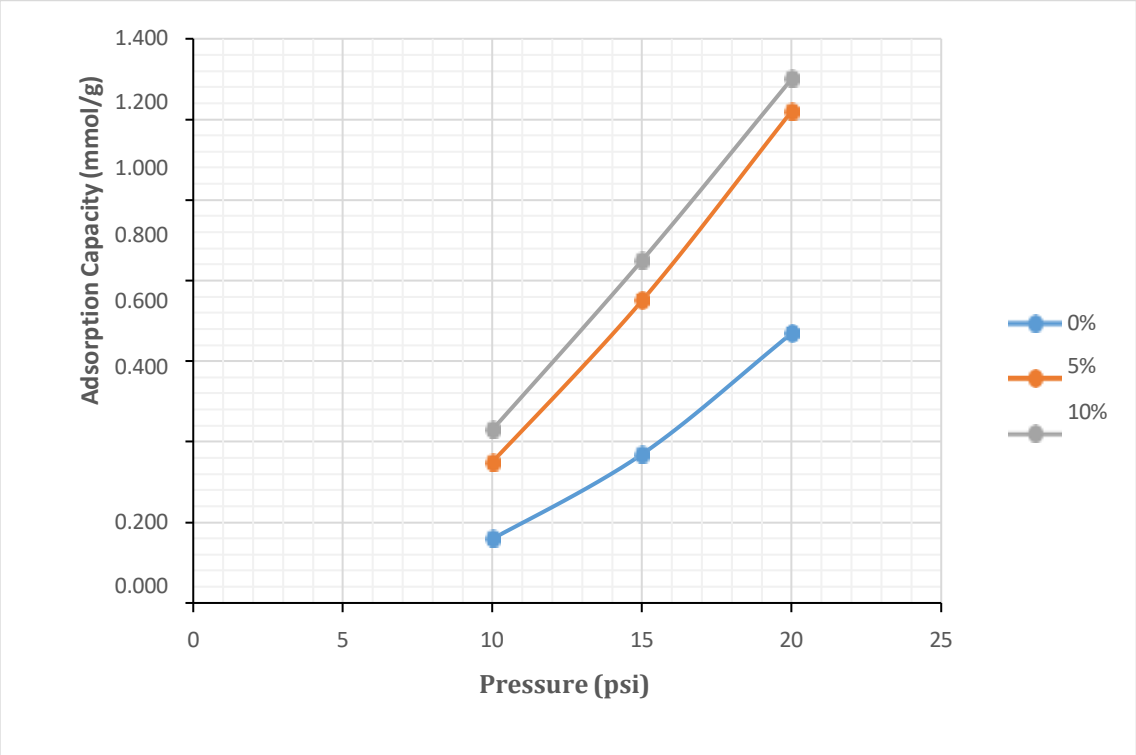



**Figure 2: Adsorption capacity for $CO_2$ of Groundnut Shell (GS) at 50°C**

### 3.1.3 Palm Kernel Shell (PKS)

Table 3 presents the cumulative adsorption capacities for PKS. PKS consistently outperformed both CS and GS. At 30°C, capacity increased from 0.755 mmol/g (dry) to 1.312 mmol/g (10% moisture) – a 73.8% improvement. At 40°C, values rose from1.279 mmol/g (0%) to 2.397 mmol/g (10%)– an 87.4% enhancement. At 50°C, the increase was from 1.100 mmol/g (dry) to 2.640 mmol/g (10% moisture) – a 140% improvement. Figure 3 (See Figure 4.9) shows this superior performance, attributed to optimal carbonization at 750°C and well-developed pore structure.

**Table 3: Cumulative $CO_2$ Adsorption Capacity of Palm Kernel Shell (PKS)**

| Temperature (°C) | 0% Moisture (mmol/g) | 5% Moisture (mmol/g) | 10% Moisture (mmol/g) |
|---|---|---|---|
| 30 | 0.755 | 1.072 | 1.312 |
| 40 | 1.279 | 1.823 | 2.397 |
| 50 | 1.100 | 1.800 | 2.640 |

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

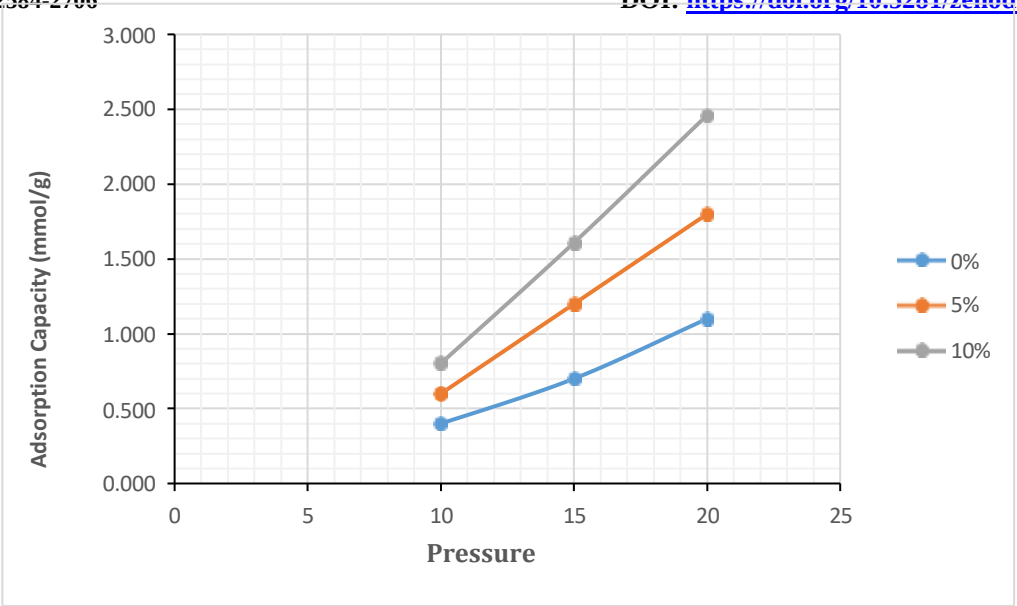



**Figure 3: Adsorption capacity for $CO_2$ of Palm Kernel Shell (PKS) at 50°C**

### 3.1.4.Comparative Analysis of Biomass Sources

Table 4 summarizes the maximum $CO_2$ adsorption capacities at 50°C and 20 psi. The ranking PKS > CS > GS held consistently. Enhancement factors (10% vs. 0% moisture) were: PKS (140%), CS (89.6%), and GS(94.3%). Figure 4 (See Figure 4.27) provides a direct visual comparison of all three adsorbents at 50°C and 10% moisture, confirming PKS as the most promising adsorbent.

| Biomass Source | 0% Moisture (mmol/g) | 10% Moisture (mmol/g) | % Enhancement |
|---|---|---|---|
| Palm Kernel Shell (PKS) | 1.100 | 2.640 | 140% |
| Coconut Shell (CS) | 1.212 | 2.298 | 89.6% |
| Groundnut Shell (GS) | 0.669 | 1.300 | 94.3% |

**Table 4: Comparative Maximum $CO_2$ Adsorption Capacities at 50°C and 20 psi**

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

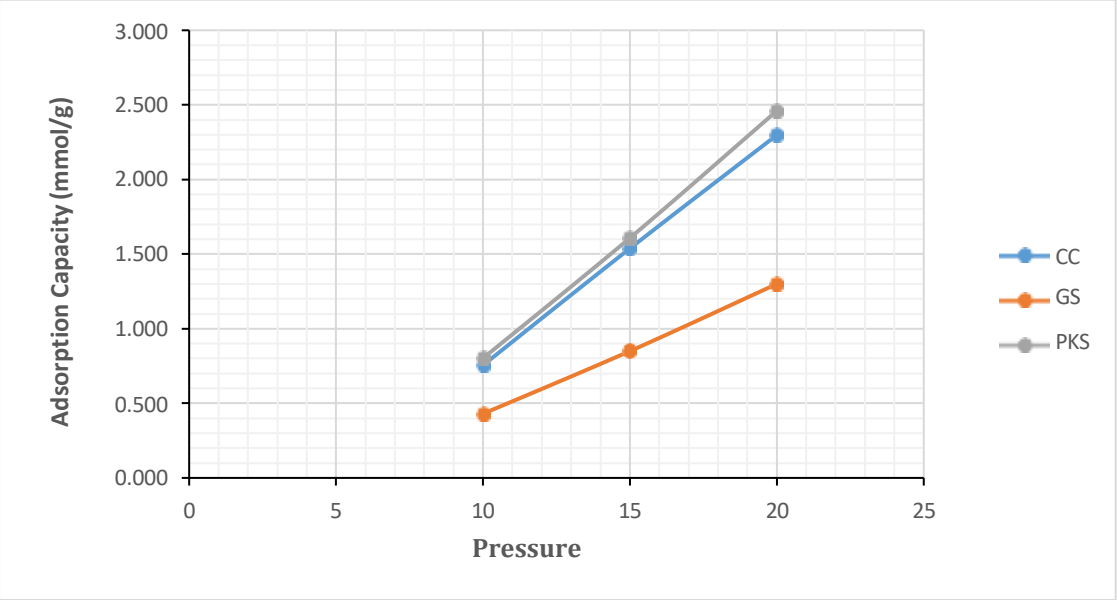



**Figure 4: Adsorption capacity for $CO_2$ of CS. GS and PKS at 50°C, 10% moisture**

## Characterization and Mechanistic Insights

### BET Surface Area Analysis

Table 5 presents the BET textural properties for dry and wet (10% moisture) PKS. Wet PKS exhibited substantially higher properties: surface area increased from237.018 to 736.79 m²/g (3.1-fold), pore volume from 1.177 to 2.853 cc/g (2.4-fold), and micropore surface area from 226.982 to690.368 m²/g (3.0-fold). These enhancements confirm that moisture prevents pore collapse and maintains open porous networks. Figure 5 (See Figures 4.28–4.33) shows the complete BET property comparison.

**Table 5: BET Textural Properties of Dry and Wet PKS**

| Parameter | Dry PKS | Wet PKS |
|---|---|---|
| Surface Area (m²/g) | 237.018 | 736.791 |
| Pore Volume (cc/g) | 1.177 | 2.853 |
| Micropore Volume (cc/g) | 0.206 | 0.613 |
| Pore Diameter (nm) | 3.040 | 3.120 |
| Pore Width (nm) | 6.670 | 7.466 |
| Micropore Surface Area (m²/g) | 226.982 | 690.368 |

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

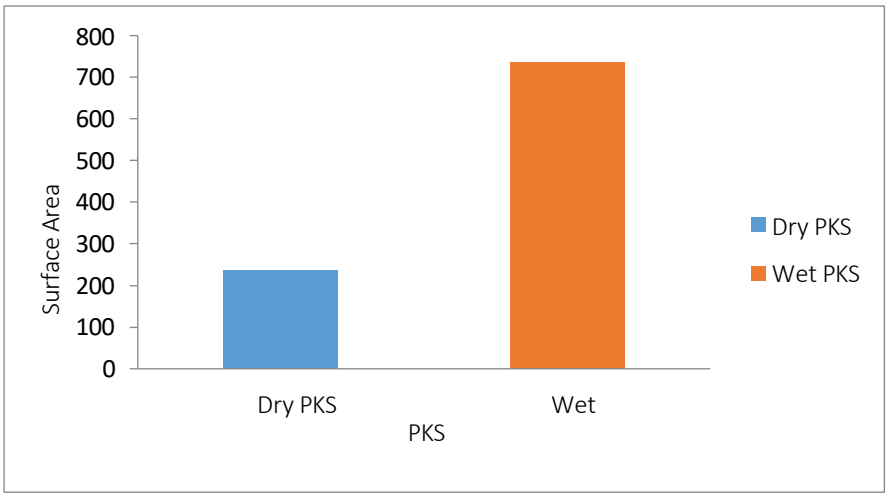



**Figure 5: Surface Area for Dry and Wet PKS**

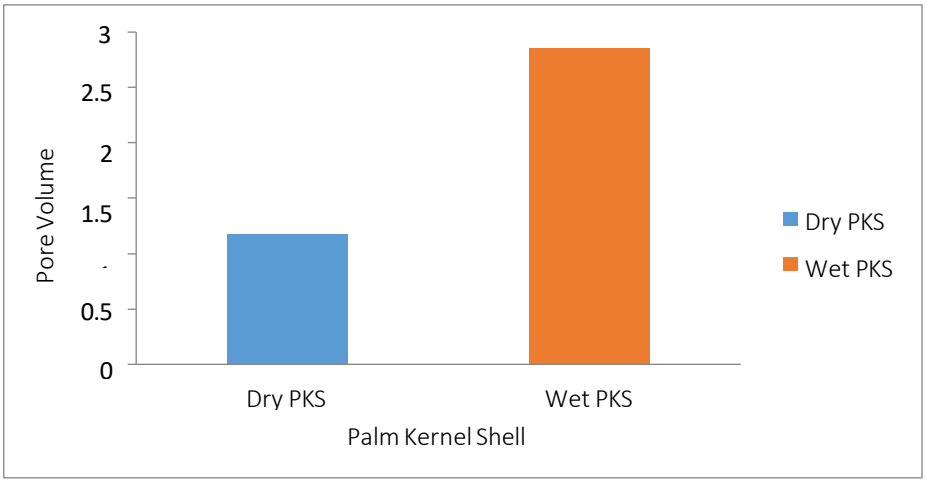
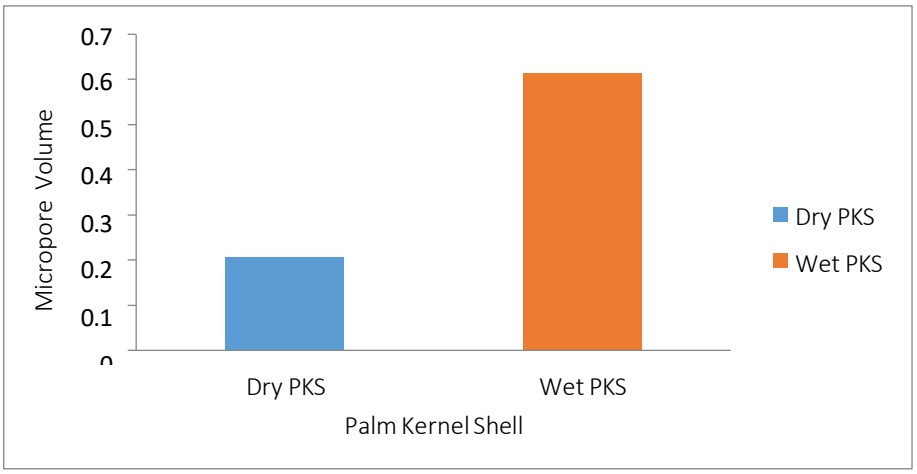



**Figure 6: Pore Volume for Dry and Wet PKS**



ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

**Figure 7: Micropore volume for Dry and Wet PKS**

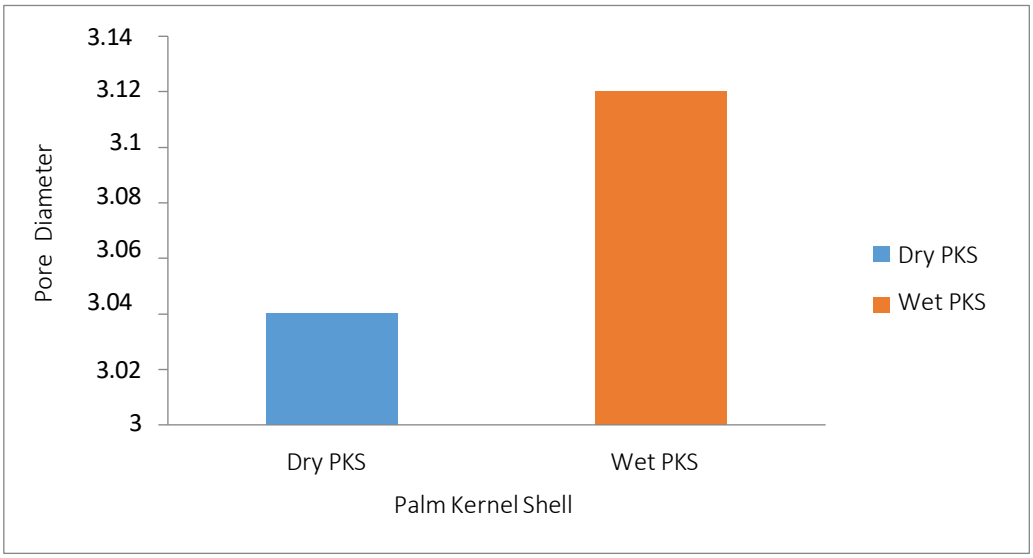



**Figure 8: Pore Diameter for Dry and Wet PKS**

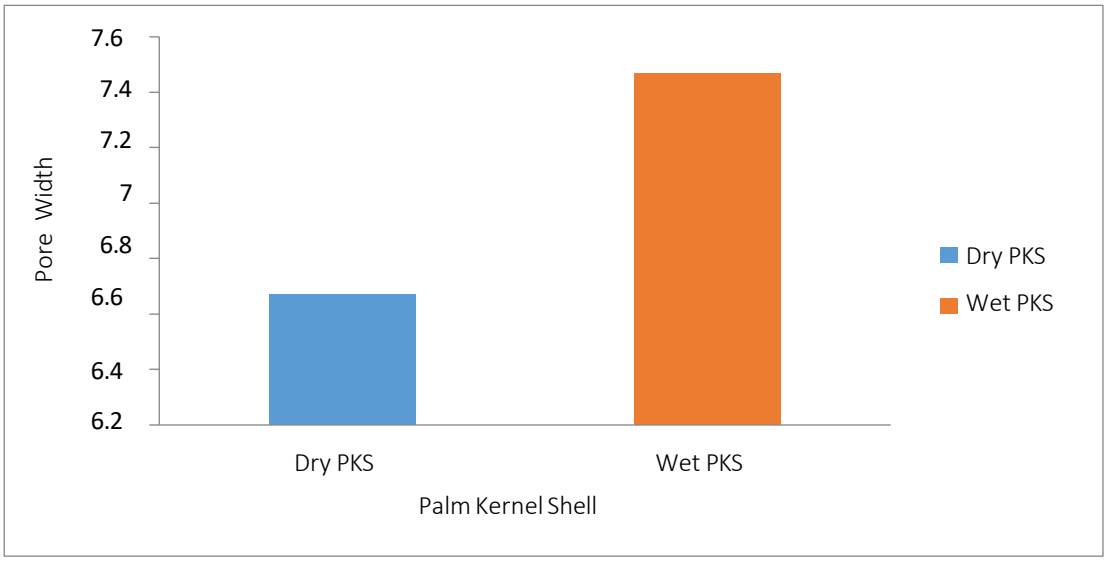



**Figure 9: Pore width for Dry and Wet PKS**

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

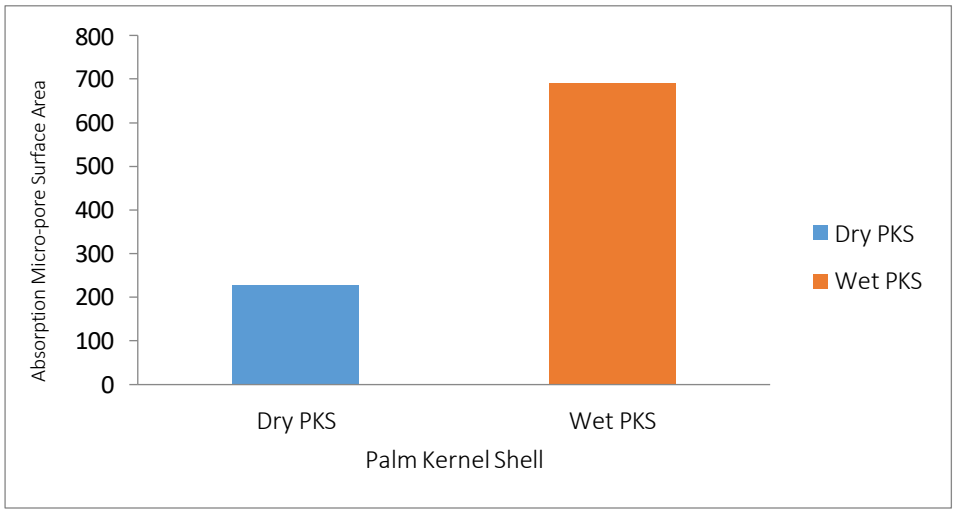



**Figure 10 : Absorption Micropore Surface Area for Dry and Wet PKS**

**FTIR Functional Group Analysis**

FTIR spectroscopy identified key surface functional groups (See Figures 4.34–4.35 in the original dissertation). Both dry and wet PKS exhibited O–H stretching vibrations (3899.8–3914 $cm^{-1}$), C–H stretching (2902–2906 $cm^{-1}$), and C=C aromatic rings (1681 $cm^{-1}$). Wet PKS additionally showed C–O stretching (1286 $cm^{-1}$), indicating oxygen-containing functional groups that provide additional adsorption sites. The presence of hydroxyl groups facilitates hydrogen bonding with $CO_2$, enhancing adsorption.

**SEM-EDX Morphology and Elemental Composition**

SEM micrographs (See Figures 4.36–4.37) revealed homogeneous pore distribution in wet PKS, with larger and more open pores compared to dry PKS. EDX analysis showed wet PKS had high carbon content (88.86 wt%) along with metal oxides (Al, Cu, Zn, Na, Mg, Si, Ca), while dry PKS contained 53.79% C and 20.09% K (residual from activation). The metal oxides contribute basic sites for $CO_2$ chemisorption..

**Proposed Enhancement Mechanisms**

The observed moisture-enhanced adsorption can be explained by:

- **Surface area and pore volume increase** – moisture prevents pore collapse during activation.
- **Hydrogen bonding** – water molecules form stable complexes with $CO_2$ [10].
- **Bicarbonate formation** – $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$, which interacts with basic surface sites [18].
- **Surface hydroxylation** – water creates O–H groups that act as additional adsorption sites [19].
- **KOH chemisorption** – residual KOH reacts with $CO_2$ and $H_2O$ to form potassium carbonate, enhancing uptake [11].

These mechanisms collectively account for the substantial increase in adsorption capacity with moderate moisture.

## 3.3.Comparison with Literature

Table 6 compares the findings with previous studies. The results align with Kelvin et al. [13] and Watana [20], who reported moisture-induced enhancement, but contrast with Yu-Chun et al. [9] and Chen et al. [8], who observed decreases at very high humidity (>60%). The findings confirm that moderate moisture (5–10%) is beneficial for KOH-activated biomass carbons.

**Table 6: Comparison of Moisture Effects on $CO_2$ Adsorption with Literature.**

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

| Author & Year | Adsorbent | Effect | Reason |
|---|---|---|---|
| This Study | PKS, CS, GS | Increase | Increased pore volume & surface area |
| Kelvin et al. [13] | Polyaspartamide | Increase | Hydration interaction |
| Yu-Chun et al. [9] | Microporous ACFs | Decrease | TEPA blocked micropores |
| Chen et al. [8] | Biochar | Decrease | Water occupied active sites |
| Watana [20] | Piperazine-impregnated | Increase | Moisture deactivated active sites |

**3.4.Summary of Key Findings**

1.Moisture Enhancement: Moderate moisture (5–10%) significantly enhances $CO_2$ adsorption, with the effect most pronounced at 50°C.
2.Biomass Ranking: PKS > CS > GS, with maximum capacities of 2.640, 2.298, and 1.300 mmol/g respectively at 50°C and 10% moisture.
3.Structural Enhancement: Wet PKS exhibited 3.1-fold higher surface area and 2.4-fold higher pore volume than dry PKS.
4.Functional Groups: FTIR confirmed O–H, C–H, C=C, and C–O groups that facilitate $CO_2$ uptake.
5.Mechanisms: Enhancement involves increased porosity, hydrogen bonding, bicarbonate formation, surface hydroxylation, and KOH chemisorption.
Practical Relevance: Supports direct use of humid flue gases without pre-dehydration.

**I.Practical Implications**

The results have significant implications for industrial $CO_2$ capture:

- Flue gas humidity (5–15%) is not detrimental but can enhance adsorption, eliminating costly pre-drying steps.
- PKS emerges as the most promising precursor due to its abundance, low cost, and superior performance.
- Optimum operating conditions are 50°C, 20 psi, and 10% moisture, which are compatible with typical flue gas conditions.
  Regeneration can be achieved by pressure or temperature swing, as adsorption is primarily physisorption-driven (reversible).
- Humidity management should aim to maintain 5–10% moisture; higher levels may cause pore blocking and should be avoided.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

## Conclusion

Moisture content was found to play a significant role in enhancing the $CO_2$ adsorption capacity of biomass-derived activated carbons, with the highest adsorption performance achieved at 10% moisture content. Among the three adsorbents investigated, palm kernel shell (PKS)-derived activated carbon exhibited the best performance, attaining a maximum adsorption capacity of 2.640 mmol $g^{-1}$ at 50°C and 20 psi, representing a 140% increase compared with the dry sample. This superior performance was supported by the physicochemical characterization results, as BET analysis revealed that moisture conditioning increased the surface area and pore volume of PKS by approximately 3.1 and 2.4 times, respectively, thereby providing a greater number of accessible adsorption sites for $CO_2$ molecules. FTIR and SEM-EDX analyses further confirmed the successful development of oxygen-containing functional groups, particularly hydroxyl (O–H) and aromatic carbon (C=C) groups, together with a homogeneous porous surface morphology that collectively enhanced the adsorption process. The improved adsorption performance under moist conditions is attributed to several synergistic mechanisms, including increased pore accessibility, hydrogen-bond interactions, bicarbonate formation, surface hydroxylation, and enhanced chemisorption promoted by KOH activation. These findings demonstrate that maintaining a moderate moisture content is advantageous for post-combustion $CO_2$ capture, eliminating the need for costly pre-dehydration of flue gases before adsorption. Consequently, activated carbon derived from palm kernel shell represents a sustainable, readily available, and cost-effective adsorbent for industrial $CO_2$ capture applications in humid flue gas environments. Future studies should investigate dynamic column breakthrough behavior, long-term cyclic adsorption–desorption stability, and pilot-scale performance under realistic industrial operating conditions.

## Reference

[1]Pachauri, R. K., & Reisinger, A. (Eds.). (2007). Climate Change 2007: Synthesis Report. IPCC, Geneva.

[2]Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (Eds.). (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press.

[3]IPCC. (2007). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report. Cambridge University Press.

[4]Siriwardane, R. V., Shen, M. S., Fisher, E.P.,& Poston, J.A.(2001). Adsorption of $CO_2$ on molecular sieves and activated carbon. Energy & Fuels, 15(2), 279–284.

[5]Zhao, R., Zhao, L., Deng, S., et al. (2017). A comparative study on $CO_2$ capture performance of vacuum-pressure swingadsorptionand pressure-temperatureswing adsorption. Energy, 137, 495–509.

[6]Nyamful, A., Nyogbe, E. K., Mohammed, I., et al. (2020). Processing and characterisation of activated carbon from coconut shell and palm kernel shell waste by $H_3PO_4$ activation. Ghana Journal of Science, 61(2), 91–104.

[7]Mustapha, O. I. (2021). Stability of Palm Kernel shell derived activated carbon for remediation. EAS Journal of Pharmacy and Pharmacology, 3(6), 168–175.

[8]Chen, C. H., et al. (2022). $CO_2$ capture over steam and KOH activated biochar: Effect of relative humidity. Biomass and Bioenergy, 166, 106608.

[9]Yu-Chun, C., Hsu, W. L., Lin, S. Y., & Juang, R. S. (2017). Enhanced $CO_2$ adsorption on activated carbon fibers grafted with nitrogen-doped carbon nanotubes. Materials, 10(5), 511.

[10]Xiao, Y., Deng, Z., & Wu, C. M. L. (2015). DFT study of carbon dioxide capture on functionalized graphane sheets. ABBE 2015, 27–27.

[11]Sahand, S. H. (2018). Carbon Dioxide Capture by Adsorption on a Biomass Based Activated Carbon. Sabancı University.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21920832

[12]Ozdemir, E., & Schroeder, K. (2009). Effect of moisture on adsorption isotherms and adsorption. International Journal of Coal Geology, 77(3-4), 315–323.
[13]Kelvin, O. Y., Amosa, M. K., Sekoai, P. T., & Daramola, M. O. (2019). Modelling and experimental investigation of effects of moisture and operating parameters during the adsorption of $CO_2$ onto polyaspartamide. International Journal of Coal Science Technology, 6(2), 225–234.
[14]Chuan, L. L., & Hing, P. S. (2017). Effect of reaction time and temperature on properties of carbon. Asian Journal of Scientific Research, 10, 24–33.
[15]Hong Zhao, & Qiongten Yu. (2019). Preparation and vapour adsorption of green walnut shell activated carbon by $CO_2$ physical activation. Yunnan Normal University, Kunning.
[16]Arash Helmi. (2013). Design and fabrication of a $CO_2$ adsorption flow loop. (details from the dissertation methodology).
[17]Jackson, P., Robinson, K., Puxty, G., & Attala, M. (2009). In-situ Fourier transform infrared analysis of carbon dioxide adsorption and desorption in amine solutions. Energy Procedia, 985–994.
[18]Wang, C., Xing, Y., Lei, Y., et al. (2021). Adsorption of water on carbon materials: the formation of "water bridge" and its effect. Colloids and Surfaces A, 631, 127719.
[19]Watana, K. (2013). Study of $CO_2$ adsorption using adsorbent modified withpiperazine.Chemical Engineering Transactions, 35.
[20]Suzuki, M. (1994). Activated carbon fiber: fundamentals and applications. Carbon, 32, 577–586.