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Adsorption of Strategic Gases on Oxygen-Functionalized CMK-8 and CMK-9 Mesoporous Carbons: Experimental and Computational Studies

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Abstract

The efficient storage of strategic gases—CH₄, CO₂, and H₂—remains a critical challenge due to the need for high pressures or cryogenic temperatures to achieve sufficient storage densities, often resulting in energy- and cost-intensive processes. Adsorption-based storage using porous materials offers a promising alternative. In particular, ordered mesoporous carbons, such as CMK-8 and CMK-9, are attractive due to their mechanical, thermal, and chemical stability, as well as their highly tunable textural properties. Surface functionalization can further enhance gas uptake, though the effect is often gas-specific. This study investigates the adsorption performance of four carbon materials: pristine CMK-8 and CMK-9, and their oxygen-functionalized counterparts produced via HNO₃ treatment. The adsorption capacities for CH₄, CO₂, and H₂ were evaluated through a combination of experimental gas adsorption measurements and molecular simulations. The results reveal structure–property relationships between surface chemistry and gas-specific adsorption behavior, with implications for the rational design of carbon-based materials for gas storage.

Keywords: adsorption; CH₄ and H₂ storage; CO₂ capture; oxygen functionalization; mesoporous carbon; textural characterization



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1. Introduction

The global demand for sustainable energy systems and greenhouse gas mitigation has intensified interest in advanced porous materials capable of efficiently capturing and storing strategic gases, including hydrogen (H₂), methane (CH₄), and carbon dioxide (CO₂) [1–3]. Porous carbons, zeolites, metal–organic frameworks, among others, have been widely investigated as adsorbents for these applications. Among these materials, carbons stand out because of their textural, chemical and thermal robustness, and the possibility of tailoring micro-mesoporosity and surface chemistry over a broad range. Within this type of material, ordered mesoporous carbons (OMC) such as CMK-8 and CMK-9 are particularly attractive, as they combine high specific surface areas with well-defined pore architectures, facilitating high working capacities for capture and gas storage [4,5]. CMK-type carbons are typically synthesized by nanocasting using mesostructured silica templates, such as KIT-6,

followed by carbonization and template removal, which yields ordered three-dimensional pore networks with a narrow pore size distribution. The interplay between micro and mesoporosity in these carbons is crucial for optimizing their performance in CO₂ capture and CH₄/H₂ storage, as narrow micropores govern adsorption at low pressure while mesopores provide transport pathways and contribute to high uptake at elevated pressure.

A key advantage of OMC lies in its highly reproducible, robust pore structure and its amenability to systematic surface functionalization. Oxidative treatments, such as nitric acid oxidation, introduce polar oxygen-containing groups (e.g., –COOH and –OH) onto the carbon framework, thereby increasing surface polarity and hydrophilicity [6,7]. For CO₂, such oxygen functionalities can enhance adsorption through a combination of specific (hydrogen bonding and electrostatic), and non-specific (dispersion) interactions, especially at low pressures, whereas for non-polar gases, such as CH₄ and H₂ the predominant effect is often related to changes in pore-size distribution and confinement [8]. However, oxidation may also partially block narrow pores or reduce accessible pore volume, with concomitant effects on diffusion and capacity. Therefore, achieving a balance between surface reactivity and pore accessibility is critical. Preserving the structural order and porosity after chemical treatment is essential for maintaining consistent performance under cyclic adsorption–desorption conditions, which are vital for practical applications in gas separation, carbon capture, and clean energy storage [9,10].

CMK-8 and CMK-9 provide a compelling platform for disentangling these effects due to their distinct morphologies and connectivity. CMK-8 features pores among rod-like structures, while CMK-9 exhibits tubular channels rather than rod-like structures. This structural contrast allows a systematic exploration of how surface chemistry and pore architecture jointly influence gas sorption behavior.

In this study, we evaluate the adsorption performance of four mesoporous carbon materials: pristine CMK-8 and CMK-9, and their oxygen-functionalized counterparts (CMK-8/O and CMK-9/O), produced via HNO₃ oxidation. Experimental characterization included Ar (87 K) and CO₂ (273 K) isotherms for textural analysis, scanning electron microscopy (SEM) for morphological characterization, thermogravimetric analysis coupled with mass spectrometry (TGA-MS) for thermal and compositional profiling, and X-ray photoelectron spectroscopy (XPS) for surface chemistry assessment. Molecular simulations offered insight into gas-surface interactions at the atomic level.

Our findings demonstrate that CMK-8 and CMK-9 respond uniquely to oxidation, with changes in microporosity, mesopore narrowing, and oxygen functional group content resulting in distinct gas storage behaviors. This study elucidates structure–function relationships in functionalized mesoporous carbons and provides design guidelines for next-generation materials for hydrogen and methane storage, as well as carbon dioxide capture under technologically relevant conditions.

2. Materials and Methods

2.1. Synthesis of the CMK-8 and CMK-9 Mesoporous Carbons

CMK-8 and CMK-9 were synthesized via nanocasting using KIT-6 silica (SiO₂) as the hard template, following a procedure previously reported by our group [11].

CMK-8 synthesis: KIT-6 (1.00 g) was gradually added to an aqueous solution of 1.86 g sucrose (C₁₂H₂₂O₁₁, Sigma-Aldrich® (Merck KGaA, Darmstadt, Germany), 99.5%), 0.21 g sulfuric acid (H₂SO₄, Sigma-Aldrich®, 98%), and 7.30 g deionized water. The mixture was stirred at room temperature for 3 h to promote infiltration of the carbon precursor into the silica pores. A two-step polymerization process was followed: 100 °C for 6 h, then 160 °C for an additional 6 h. A second impregnation was carried out using a fresh solution of 1.17 g sucrose, 0.13 g sulfuric acid, and 7.30 g water, followed by identical thermal treatment.

The resulting composite was carbonized under nitrogen (180 mL/min) at 900 °C for 4 h (heating rate: 3 °C/min). Silica was removed by leaching in 5% hydrofluoric acid at room temperature with continuous stirring for 24 h. The resulting carbon was washed several times with a 1:1 (v/v) mixture of water and ethanol, and then dried at 80 °C for 12 h.

CMK-9 synthesis: A mixture of 1.94 g furfuryl alcohol (C₅H₆O₂, Sigma-Aldrich®, 98%), 3.47 g 1,3,5-trimethylbenzene (C₉H₁₂, Sigma-Aldrich®, 98%), and 0.017 g oxalic acid (C₂H₂O₄, Biopack® (Buenos Aires, Argentina), 99.5%) was stirred at room temperature for 30 min and then added to 1.00 g KIT-6 silica. The mixture was stirred using a rotary evaporator at 35 °C for 2 h. Polymerization was performed in two steps: 60 °C for 16 h, followed by 80 °C for an additional 16 h. Carbonization was carried out under nitrogen flow (180 mL/min) in three stages: (i) 1 °C/min to 150 °C (hold 3 h), (ii) 1 °C/min to 300 °C, and (iii) 3 °C/min to 900 °C (hold 4 h). Silica removal and post-treatment followed the same procedure as for CMK-8.

2.2. Chemical Oxidation of CMK-8 and CMK-9

Surface oxidation was performed using 4 M nitric acid (HNO₃, Sigma Aldrich®, 65%). Each carbon sample (1.00 g) was suspended in 50 mL of HNO₃ and stirred at 50 °C (200 rpm) for 1 h. The solids were filtered and washed with deionized water until the filtrate conductivity fell below 10 µS/cm. The oxidized carbons (CMK-8/O and CMK-9/O) were dried at 60 °C for 12 h.

2.3. Characterization Techniques

Scanning SEM: Scanning electron microscopy images were acquired using an FEI Quanta 200 microscope (Thermo Fisher, Waltham, MA, USA). Samples were coated with a ~10 nm gold layer before imaging, performed at 15 kV.

TGA-MS: Thermogravimetric analysis was performed on a TA Instruments SDT Q600 thermal analyzer (TA Instruments, New Castle, DE, USA) coupled with a Discovery mass spectrometer (TA Instruments, New Castle, DE, USA). Samples (~4 mg) were placed in alumina pans and analyzed under a N₂ flow (100 mL/min) from room temperature to 1000 °C at 10 °C/min.

XPS: X-ray photoelectron spectra were collected on a Physical Electronics PHI 5701 spectrometer (Physical Electronics, Chanhassen, MN, USA) using non-monochromatic Mg K α radiation (1253.6 eV, 300 W, 15 kV). Analyses were performed at a pass energy of 29.35 eV. Charge referencing was performed against the C 1s peak (284.8 eV). Spectra were fitted with Gauss–Lorentz functions using PHI ACCESS ESCA-V6.0 F and Multipak v8.2b software.

Gas adsorption and porosity: Ar adsorption–desorption isotherms at 87 K and H₂ adsorption (up to 1 bar) at 77, 90, and 105 K were measured using an Autosorb iQ analyzer (Quantachrome Instruments, Boynton Beach, FL, USA) with a CTI Cryogenics cryocooler (Edwards Vacuum, Burgess Hill, UK). Samples were degassed before measurement (150 °C for pristine, 60 °C for oxidized carbons, 12 h). Analyses were performed with 120 mg of material. The specific surface area (S_{BET}) was determined utilizing the Brunauer, Emmet, and Teller method [12]. The total pore volume (V_{TP}) was calculated using Gurvich's rule at $p/p^0 = 0.98$ [13]. Micropore volume ($V_{\mu\text{P-Ar}}$) was derived from Ar isotherms. Pore size distributions (PSD) were determined using the ASiQwin software (version 4.0 Build:10) from Quantachrome Instruments, employing the Quenched Solid Density Functional Theory (QSDFT) method (Ar at 87 K on carbon, cylindrical pores, adsorption branch) [14].

CO₂ adsorption isotherms were measured at 273 K up to 10 bar using a manometric Micromeritics ASAP 2050 analyzer (Micromeritics, Norcross, GA, USA). Micropore size distributions were determined using the Horvath-Kawazoe (HK) method for slit pores [15].

Water sorption-desorption isotherms were measured at 298 K using a VTI SGA-100 gravimetric sorption analyzer (TA Instruments, New Castle, DE, USA) with Dynamic Vapor Sorption, employing dry air as the carrier gas. Approximately 5 mg of the sample was used for each analysis. Pristine CMK-8 and CMK-9 were degassed under a dry air flow at 80 °C until reaching equilibrium, with a variation of less than 1 µg over 10 min. The oxidized samples were degassed at 60 °C under the same equilibrium conditions.

2.4. CO₂, CH₄ and H₂ Gas Storage Measurements

Adsorption isotherms of CO₂ (purity 99.996%) at 308 K, CH₄ (purity 99.995%) at 298 K, and H₂ (purity 99.999%) at 77 K were performed up to 10 bar, using a Micromeritics ASAP 2050 sorption analyzer (Micromeritics, Norcross, GA, USA). Thermal baths for CO₂ and CH₄ were maintained using a Julabo F25 recirculating cooler (JULABO GmbH, Seelbach, Germany), and H₂ was maintained at liquid nitrogen temperature. All the samples were degassed under the same conditions used in Ar adsorption.

2.5. Isostatic Enthalpy of Adsorption

The isosteric enthalpy of adsorption ($\Delta_{Ads}h$) provides insight into the strength of gas-surface interaction, adsorption mechanisms, and surface heterogeneity. Values of ($\Delta_{Ads}h$) for each gas were derived from isotherms collected at different temperatures (see Figure S1), CO₂ at 273 K and 308 K, CH₄ at 298 K and 313 K, and H₂ at 77 K, 90 K, and 105 K, using the Clausius-Clapeyron equation [16]:

$$\Delta_{Ads}h = R \cdot \left[\frac{\partial \ln p}{\partial \ln T} \right]_{n_{ads}} \quad (1)$$

where p is the equilibrium pressure, T is the adsorption absolute temperature, and R is the universal gas constant (8.314 kJ/(mol·K)). The isosteric enthalpy of adsorption at a specific gas uptake was determined from the slope of adsorption isosteres ($\ln p$ vs. $1/T$) at constant gas uptake.

2.6. Computational Approach

The physisorption of CH₄, CO₂, and H₂ at supercritical conditions occurs through a combination of van der Waals and Coulomb interactions between the adsorbent and the adsorbate [17]. As it does not involve proper chemical bonding, the adsorption is reversible and generally non-specific [18,19]. However, due to its significant electric quadrupole moment, CO₂ exhibits a preference for adsorption sites near polar surface groups [20].

To investigate adsorption mechanisms at the atomic level, Grand Canonical Monte Carlo (GCMC) simulations were conducted, which are particularly suitable for modeling gas adsorption in porous materials [21–23]. A slit-shaped pore geometry was employed, modeled by two parallel graphene-like surfaces separated by a distance H in the z -direction. Note that H corresponds to the distance between idealized planes of graphene, which is approximately one carbon atom collision diameter (~3.5 Å) larger than experimentally measured pore sizes.

Simulations were performed for $H = 8, 10, 12, 15$, and 30 Å, using two surface types: (i) a pristine graphene surface (denoted GP), and (ii) a graphene oxide surface containing hydroxyl (–OH) and epoxy (–O–) groups (denoted GOx). GP was modeled as a standard graphene honeycomb lattice, with a base unit cell of 140 carbon atoms forming a rectangular domain of $l_x = 21.300$ Å by $l_y = 17.217$ Å, as shown in Figure 1. A simulation box of $2 \times 2 \times 3$ unit cells (total 1680 C atoms) was used. For GOx, 12 hydroxyl and 12 epoxy groups were pseudo-randomly introduced (~14% O content), matching the experimentally observed oxygen content (~13%) for CMK-8/O and CMK-9/O.

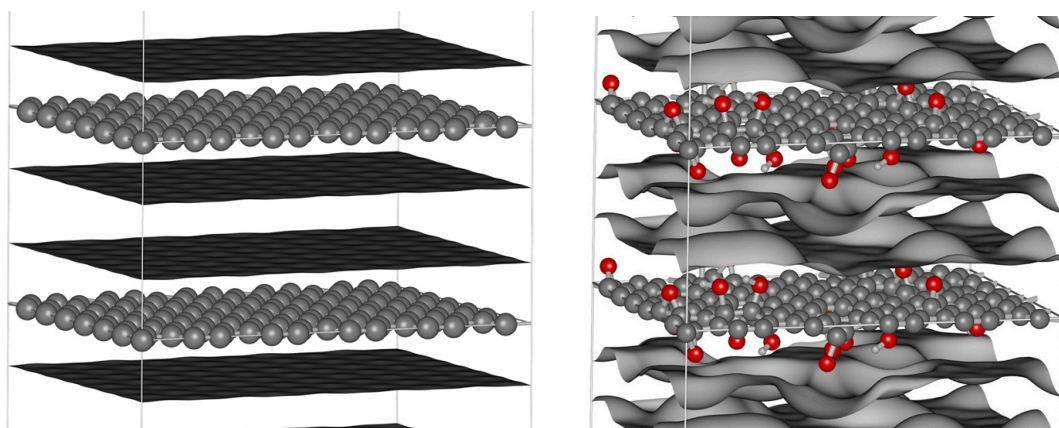


Figure 1. Base unit cells of GP (**left**) and GOx (**right**) for $H = 12 \text{ \AA}$. Color scheme: C = gray, O = red, H = light gray. Additional surfaces shown separate the accessible and inaccessible volumes for a CH_4 or CO_2 molecule.

Before simulations, GOx structures were partially optimized using Density Functional Theory (DFT) with the B3LYP functional and 6-31G(d,p) basis set [24–27] via Gaussian 16 [28]. DFT results provided atomic coordinates, Mulliken charges, and bonded force constants [28]. Notably, carbon atoms bonded to oxygen groups were slightly displaced from the graphene plane due to altered hybridization, as shown in Figure 1. Non-bonded interactions were defined using parameters derived from the Universal Force Field (UFF) [29–31] and CGenFF [32,33]. Crystallographic Information Files (CIFs) are provided in the Supplementary Materials.

GCMC simulations were performed using the RASPA2 [34] code. Periodic boundary conditions were applied in all directions, with the simulation box comprising $2 \times 2 \times 3$ replicas of the unit cell $l_x \times l_y \times H$, i.e., $L_x \times L_y \times L_z = 42.600 \text{ \AA} \times 34.434 \text{ \AA} \times 3H$, consistent with the requirement of an interaction cut-off $r_c \leq \frac{1}{2} \min(L_x, L_y, L_z)$ [35]. We employed Universal Force Field (UFF) [29–31] potentials. Lorentz-Berthelot combination rules were used for mixed-species Lennard-Jones (LJ) interactions. Electrostatics were treated using the particle-mesh Ewald (PME) method [36] under periodic boundary conditions. This approach is particularly important for capturing the quadrupolar interactions of CO_2 with oxygen-containing surface groups, while ensuring consistent treatment of electrostatics in all simulated systems.

Molecular models were defined as follows. Methane was modeled in the United Atom Approximation (UAA) as a spherical particle with mass $m = 16.04246 \text{ amu}$ and LJ parameters $\epsilon = 148.0 \text{ K}$ and $\sigma = 3.73 \text{ \AA}$ [18,37–45]. Carbon dioxide was modeled as a rigid structure with $m_{\text{O}} = 15.9994 \text{ amu}$, $m_{\text{C}} = 12.0000 \text{ amu}$, $q_{\text{O}} = -0.33 e$, $q_{\text{C}} = +0.66 e$, and distance between C and O $d_{\text{CO}} = 1.149 \text{ \AA}$, which results in an electric quadrupole moment $Q_{zz}^{\text{CO}_2} = -13.9 \times 10^{-40} \text{ C}\cdot\text{m}^2$, comparable to experimental values -14×10^{-40} to $-15 \times 10^{-40} \text{ C}\cdot\text{m}^2$ [20]; LJ parameters employed are $\epsilon_{\text{O}} = 79.0 \text{ K}$, $\sigma_{\text{O}} = 3.05 \text{ \AA}$, and $\epsilon_{\text{C}} = 27.0 \text{ K}$, $\sigma_{\text{C}} = 2.80 \text{ \AA}$. Hydrogen molecules were modeled as two atoms of $m_{\text{H}} = 1.00794 \text{ amu}$, charge $q_{\text{H}} = 0.42 e$ with a separation of $d_{\text{HH}} = 0.71 \text{ \AA}$ but no LJ interactions, and an additional massless “ghost” atom $m_{\text{COM}} = 0$, charge $q_{\text{COM}} = -0.84 e$, and LJ parameters $\epsilon_{\text{COM}} = 36.7 \text{ K}$, $\sigma_{\text{COM}} = 2.96 \text{ \AA}$. This results in an electric quadrupole moment $Q_{zz}^{\text{H}_2} = +1.84 \times 10^{-40} \text{ C}\cdot\text{m}^2$, comparable to experimental $+1.73 \times 10^{-40}$ to $2.21 \times 10^{-40} \text{ C}\cdot\text{m}^2$ [46]. Note that although H_2 has a quadrupole moment, it is 11 times smaller than that of CO_2 . A united-atom model was also tested for comparison with a single “superatom” $m_{\text{H}_2} = 2.01588 \text{ amu}$, and $\epsilon_{\text{H}_2} = 36.7 \text{ K}$, $\sigma_{\text{H}_2} = 2.96 \text{ \AA}$.

Surface atoms had the following parameters: pristine C atoms were neutral with LJ parameters $\varepsilon_C = 35.23$ K, $\sigma_C = 3.55$ Å [18,38–41]. C atoms bonded to –OH or epoxy groups carried partial charges of $+0.215 e$ and $+0.221 e$, respectively. OH groups: O = $-0.601 e$, H = $+0.386 e$; epoxy O = $-0.442 e$. All systems were electrically neutral. Helium void fractions (X_{He}) were computed using Widom-Rosenbluth insertion in RASPA2 to estimate the excess adsorption [34].

Simulations were conducted at pressures $P = 0.2, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30$, and 60 bar. Each run included 1000 initialization cycles for equilibration (verified by monitoring the system energy—in all cases equilibration was reached by 50% of the initialization part of the simulation), followed by 5000 sampling cycles. Each cycle consisted of at least 100 or the number of adsorbed molecules GCMC steps. Move types (translation, rotation, insertion, deletion) were attempted with equal probabilities. Acceptance probabilities followed standard Metropolis criteria [21–23]:

$$P_{\text{accept}} = \begin{cases} \min(1, e^{-\beta(U_{\text{new}} - U_{\text{old}})}), & \text{translation, rotation,} \\ \min(1, \frac{\Lambda^3 N}{V} e^{-\beta(U_{\text{new}} - U_{\text{old}} + \mu)}), & \text{annihilation,} \\ \min(1, \frac{V}{\Lambda^3 (N+1)} e^{-\beta(U_{\text{new}} - U_{\text{old}} - \mu)}), & \text{creation,} \end{cases} \quad (2)$$

where $\beta = 1/(k_B T)$ is the reciprocal temperature, $\Lambda = h/(2\pi m k_B T)^{1/2}$ is the thermal wavelength [21–23], μ is the chemical potential, and U is the potential energy of the system. We use the ideal gas approximation $P \approx k_B \Lambda^3 \cdot e^{\beta\mu}$, introducing negligible error under supercritical conditions.

RASPA2 provided values for absolute adsorption (N_a), excess adsorption ($N_e = N_a - V \cdot X_{\text{He}} \cdot \rho_{\text{gas}}$), and the isosteric enthalpy of adsorption ($\Delta_{\text{Ads}} \dot{h}$) via fluctuation theorem [23,37]:

$$\Delta_{\text{Ads}} \dot{h} = k_B \cdot T - \frac{\langle NE \rangle - \langle N \rangle \langle E \rangle}{\langle N^2 \rangle - \langle N \rangle^2}, \quad (3)$$

where N and E are the number of adsorbed molecules and system energy, respectively.

For each structure, adsorbent, and pressure, we set the RASPA2 code to save the positions of every atom every 50 cycles (i.e., 100 frames, the large number of GCMC steps between frames guarantees each frame to be statistically independent of earlier frames). From these frames, the radial pair distribution function [22,47] $g(r)$ may be computed for any pair of types of atoms, allowing detailed analysis of fluid-fluid or fluid-surface interactions. Notably, peaks in $g(r)$ between polar O atoms and adsorbates such as CO₂ provide insight into adsorption mechanisms driven by quadrupolar interactions.

All simulation parameters, molecular models, force fields, and raw data summaries are provided in the Supplementary Materials.

3. Results and Discussion

3.1. Morphological Characterization

SEM micrographs (Figure 2) show that CMK-8 and CMK-9 materials exhibit rod-like morphologies with tortuous, interconnected structures characteristic of carbons synthesized from cubic mesostructured silica templates [48]. Upon surface oxidation with nitric acid, no substantial morphological alterations were observed in either material, indicating that the acid treatment preserved the external architecture and particle integrity. This structural stability is particularly relevant for gas adsorption applications, as it ensures the accessibility and uniformity of the porous network without inducing macroscopic collapse or agglomeration. The elongated, contorted rod-like features are expected to promote efficient gas diffusion throughout the porous matrix, a factor of particular interest for optimizing the uptake kinetics of small gas molecules such as CO₂, CH₄, and H₂.

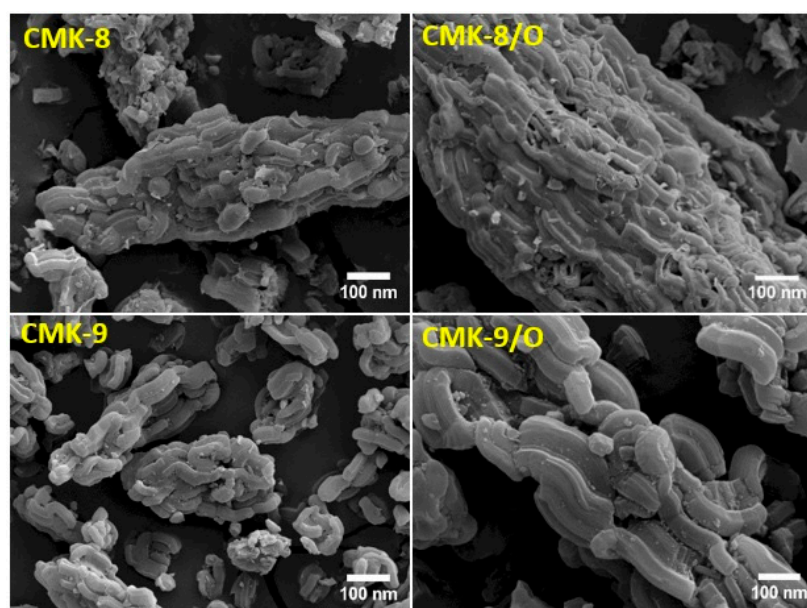


Figure 2. SEM images of pristine and modified CMK-8 and CMK-9 carbon materials.

3.2. Structural Characterization

Figure 3 presents the thermal analysis results of CMK-8 and oxidized CMK-8 (CMK-8/O), including thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) profiles and associated mass spectra ($m/z = 18$ and 44). In all cases, an initial mass loss is observed below $100\text{ }^{\circ}\text{C}$, which is attributed to the desorption of physisorbed water. This loss is more pronounced in the oxidized sample, indicating an increased affinity for water formation during the thermal process due to the introduction of polar oxygen-containing functional groups. This trend is further supported by the increased intensity of the $m/z = 18$ signal (H_2O), reflecting a higher degree of hydrophilicity resulting from the acid treatment. In pristine CMK-8 (Figure 3a), the DTG curve exhibits two well-defined thermal events within the temperature ranges of $414\text{--}520\text{ }^{\circ}\text{C}$ (1.1%) and $520\text{--}624\text{ }^{\circ}\text{C}$ (2.3%). These events are associated with the decomposing residual oxygen-containing groups that were not completely removed during carbonization. In parallel, the mass spectrum (Figure 3b) shows signals at $m/z = 18$ and 44 , indicating the concurrent release of water and carbon dioxide, typical decomposition products of carboxylic acids, lactones, and carboxylic anhydrides [49]. After oxidative treatment with HNO_3 (CMK-8/O, Figure 3c), the material exhibits five distinct mass loss events above $80\text{ }^{\circ}\text{C}$. The first two, occurring within $87\text{--}210\text{ }^{\circ}\text{C}$ and $210\text{--}425\text{ }^{\circ}\text{C}$, correspond to mass losses of 1.3% and 3.5%, respectively. A broad CO_2 signal ($m/z = 44$) is observed within these temperature ranges, related to the loss of carboxylic acid groups. Variation in decomposition temperatures may be attributed to differences in the acidity of functional groups: more acidic groups decompose at lower temperatures, whereas less acidic groups require higher temperatures [50]. Additionally, three further thermal events were identified in the $425\text{--}513\text{ }^{\circ}\text{C}$, $513\text{--}614\text{ }^{\circ}\text{C}$, and $614\text{--}853\text{ }^{\circ}\text{C}$, associated with mass losses of 1.7%, 2.8%, and 4.2%, respectively. Based on the intensity and evolution of the $m/z = 44$ signal, the first two events are attributed to the decomposition of lactones. At the same time, the third is assigned to the degradation of carboxylic anhydrides.

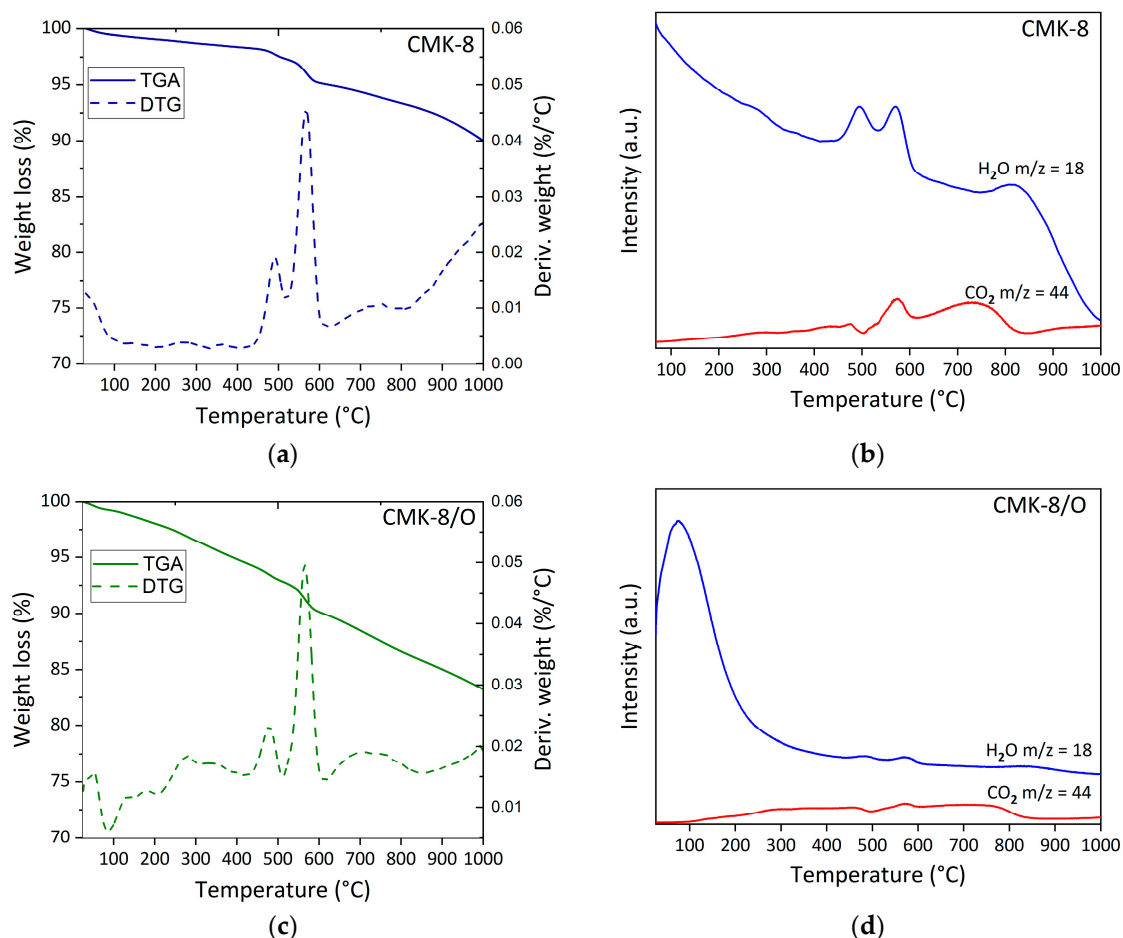


Figure 3. Thermal analysis of carbon materials: (a) TG-DTG curves of CMK-8; (b) mass spectrometry (MS) signals ($m/z = 18$ and 44) evolved during TGA of CMK-8; (c) TG-DTG curves of oxidized CMK-8 (CMK-8/O); (d) MS signals ($m/z = 18$ and 44) evolved during TGA of CMK-8/O.

Figure 4 shows the TGA-DTG-MS analysis results for the pristine CMK-9 and its oxidized analog (CMK-9/O). Both samples exhibit the typical initial event corresponding to the desorption of physisorbed water below 100 °C, which is again more pronounced in the oxidized sample, consistent with its lower hydrophobic character. In pristine CMK-9 (Figure 4a), four thermal events were identified following the initial water loss: 138–216 °C (0.3%), 216–446 °C (0.7%), 446–600 °C (0.9%), and 600–756 °C (1.4%). These events are assigned to the desorption of strongly retained water, the elimination of carboxylic groups, and the decomposition of lactones and anhydrides. The total mass loss in CMK-9 (6.6%) was notably lower than that observed for pristine CMK-8 (10%), suggesting a lower density of surface functional groups in CMK-9. This difference may be related to the type of carbon precursor used during synthesis. While CMK-8 was derived from sucrose, a source rich in hydroxyl and oxygen-containing groups, CMK-9 was synthesized from furfuryl alcohol, a more aromatic and less oxygenated compound [51,52]. This fact can influence both the surface chemistry of the resulting carbon and the incorporation of heteroatoms during carbonization. After oxidation with HNO₃, CMK-9/O (Figure 4c) exhibited a more complex thermal profile, with five well-defined events: 92–125 °C (0.5%), 125–200 °C (1.0%), 200–494 °C (5.8%), 494–583 °C (1.7%), and 582–900 °C (6.4%). The first three are attributed to water desorption and the removal of carboxylic groups. In contrast, the last two are associated with the degradation of lactones and anhydrides, as evidenced by the intensified $m/z = 18$ and 44 signals (Figure 4d). The total mass loss in CMK-9/O reached 17%, a value similar to that observed in CMK-8/O (16.7%). However, analysis of the specific

thermal ranges reveals differences in the type of oxygenated functional groups present. Notably, the mass loss observed up to 450 °C was significantly higher in CMK-9/O (7.3%) than in CMK-8/O (4.8%), suggesting a higher density of surface carboxylic groups, which typically decompose within this temperature range [49,53]. At intermediate temperatures (450–650 °C), associated with the removal of phenols, carbonyls, or quinones, CMK-8/O exhibited a greater loss (4.6%) than CMK-9/O (1.7%). Finally, at temperatures above 600 °C, corresponding to the decomposition of lactones and anhydrides, CMK-9/O exhibited a greater loss (6.4%) than CMK-8/O (4.2%). These results indicate that CMK-9/O exhibits a surface functionalization enriched in strongly acidic and polar groups, such as carboxylic acids and anhydrides, suggesting a higher acidic character and potentially greater affinity for polar molecules, such as CO₂.

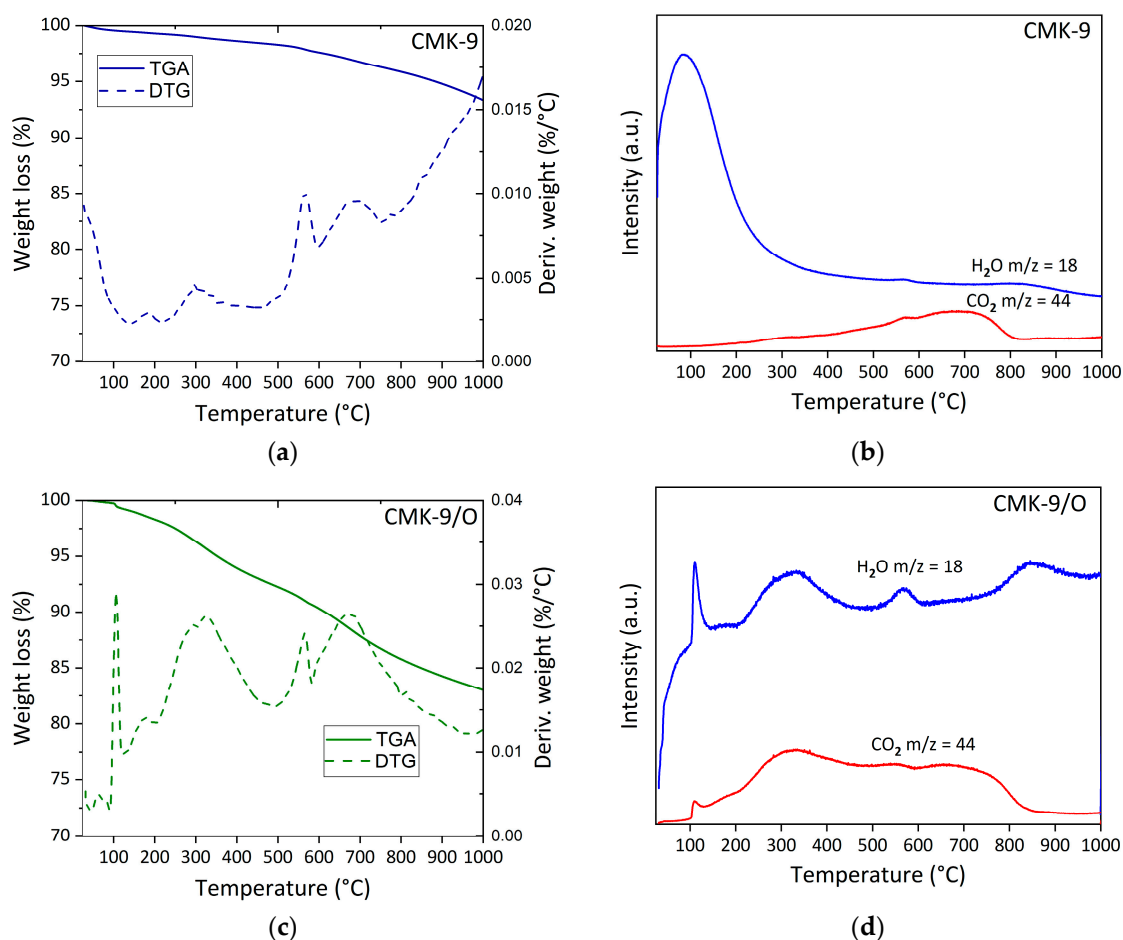


Figure 4. Thermal analysis of carbon materials: (a) TG-DTG curves of CMK-9; (b) mass spectrometry (MS) signals ($m/z = 18$ and 44) evolved during TGA of CMK-9; (c) TG-DTG curves of oxidized CMK-9 (CMK-9/O); (d) MS signals ($m/z = 18$ and 44) evolved during TGA of CMK-9/O.

3.3. Surface Characterization

The high-resolution XPS spectra for the C 1s and O 1s core levels of CMK-8 and its oxidized counterpart (CMK-8/O) (Figure 5a,b) reveal the surface chemical changes induced by HNO₃ oxidation. In the C 1s spectrum of CMK-8, a dominant peak is observed at 284.7 eV, characteristic of C–C/C=C bonds present in graphitic structures, representing 90.86% of the total C 1s area [54]. In CMK-8/O, this peak remains the most intense (91.48%); however, new components appear at 285.8 eV (C–O, 4.39%) and 288.2 eV (O=C–O, 4.13%), which are attributed to hydroxyl/ether and carboxylic acid groups, respectively [55]. The relatively low intensity of these latter signals suggests a moderate degree of surface

functionalization. This observation is further supported by the O 1s spectra, where CMK-8 exhibits two distinct contributions at 532.5 eV (91.75%) and 530.1 eV (8.25%). The former is assigned to oxygen in C–O environments, typical of hydroxyl, ether, or phenolic groups, while the lower binding energy component at 530.1 eV may correspond to oxygen in carbonyl groups (C=O), such as ketones or quinones, often located at defective edges of the carbon framework [56].

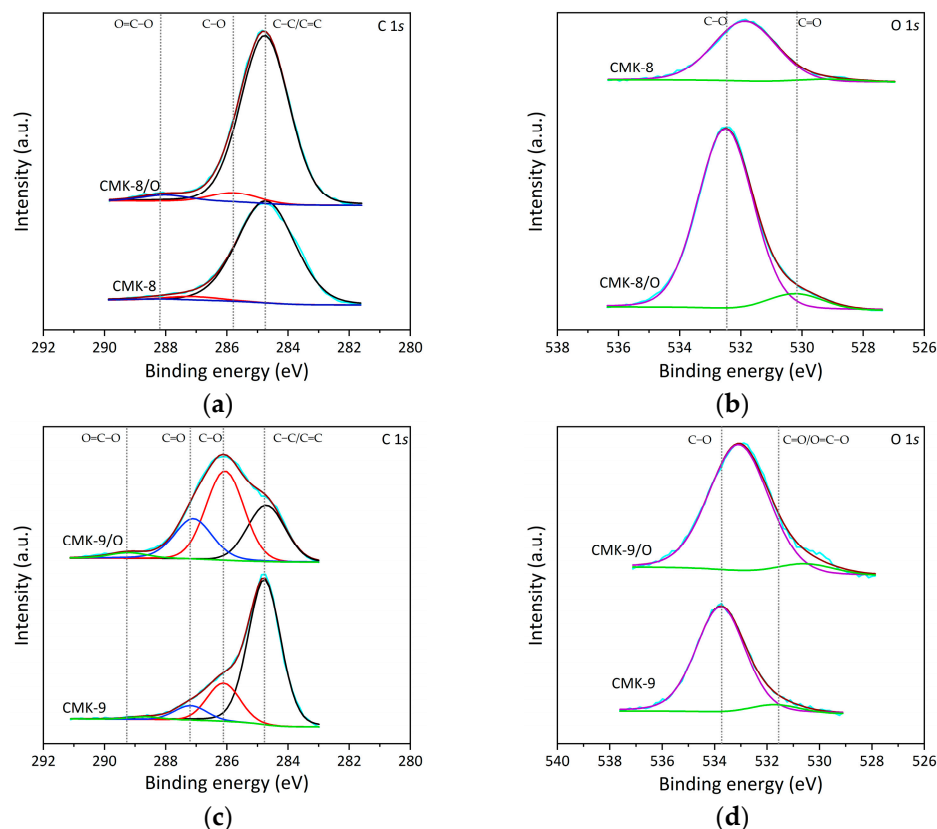


Figure 5. High-resolution core-level XPS spectra of: (a) C 1s and (b) O 1s of CMK-8 and CMK-8/O; (c) C 1s and (d) O 1s of CMK-9 and CMK-9/O. CMK-8 and CMK-9 were previously reported [11].

In contrast, the O 1s spectrum of CMK-8/O displays a main peak centered at 532.5 eV, accounting for 86.70% of the total O 1s area, and likely representing a convolution of predominantly carbonyl (C=O) and carboxyl (O=C–O) species, whose binding energies are close and may overlap. A single broad contribution suggests that these functional groups are in a chemically similar or structurally disordered environment. These findings are consistent with the TGA-MS analysis, which showed that CMK-8/O exhibited mass loss attributable to acidic surface functionalities. From a gas adsorption perspective, the introduction of oxygen-containing groups in CMK-8/O is expected to enhance interactions with polar gases such as CO₂ through acid-base interactions and hydrogen bonding without significantly affecting the affinity toward non-polar gases like CH₄ or H₂, which primarily interact via van der Waals dispersion forces.

The XPS spectra of CMK-9 and its oxidized form (CMK-9/O) reveal more pronounced changes upon oxidation (Figure 5c,d). In the C 1s spectrum of CMK-9, the main component is centered at 284.7 eV, corresponding to C–C/C=C bonds (75.85%), similar to that observed in CMK-8. Well-resolved additional peaks appear at 286.1 eV, assigned to C–O bonds (17.81%), and at 287.2 eV, attributed to carbonyl (C=O) functionalities (6.34%). Upon oxidation, the CMK-9/O spectrum shows a clear redistribution of components: the most intense peak shifts to 286.0 eV (C–O, 43.55%), indicating an increase in oxygenated surface

groups, followed by peaks at 284.7 eV (C–C/C=C, 27.68%), 287.1 eV (C=O, 24.33%), and a weaker contribution at 289.2 eV, which is associated with carboxylic and anhydride groups (O–C=O, 4.43%) [57,58]. This distribution suggests a more diverse surface functionalization compared to CMK-8/O. A similar trend is evident in the O 1s spectra. For CMK-9, two main peaks are observed: one at 533.7 eV, corresponding to oxygen in C–O environments (alcohols, ethers, 91.25%), and another at 531.6 eV, related to oxygen in carbonyl groups (C=O, 8.25%). In the oxidized sample, CMK-9/O, these bands shift slightly to lower binding energies, appearing at 533.1 eV (C–O, 90.31%) and 530.4 eV (C=O/O–C=O, 9.69%), suggesting a more functionalized chemical environment, and possibly a slight decrease in the energetic stability of the oxygen-containing bonds. These findings align with the TGA-MS results, which show that CMK-9/O exhibits the highest mass loss associated with the decomposition of carboxylic and anhydride groups. The enrichment in oxygen functionalities provides more active sites for interaction with CO₂, enhancing its adsorption via acid-base interactions and increasing surface polarity. In contrast, for CH₄ and H₂, gases whose adsorption is dominated by weak physical interactions, the effect may be more limited; however, the highly developed and open porous texture of CMK-9 could still promote their diffusion and retention. These features present CMK-9/O as a versatile candidate for polar and non-polar gas adsorption, highlighting its potential for gas separation and storage applications.

3.4. Textural Characterization

3.4.1. Argon Adsorption–Desorption Isotherms at 87 K

Argon adsorption–desorption isotherms at 87 K for the materials under study are shown in Figure 6. All materials exhibit Type IV(a) isotherms according to the International Union of Pure and Applied Chemistry (IUPAC) classification, a characteristic of micro-mesoporous materials. The hysteresis loops, indicative of mesoporosity, correspond to Type H4 for the CMK-8 materials and Type H2(a) for the CMK-9 materials [59], suggesting differences in pore morphology between both series. Also, a narrower hysteresis loop is observed in the samples corresponding to the CMK-9 materials. At high relative pressures ($p/p^0 \approx 1$), no significant increase in the adsorbed amount is observed in all isotherms, indicating no significant contribution from macropores. In both CMK-8 and CMK-9 materials, the adsorption isotherms of the pristine samples and the oxygen-functionalized ones exhibit a similar shape, with the isotherm of the pristine samples remaining consistently above that of the functionalized one across the entire range of relative pressures.

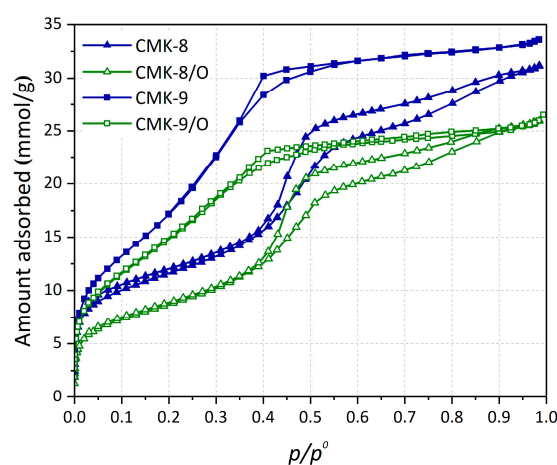


Figure 6. Ar adsorption–desorption isotherms at 87 K for CMK-8, CMK-9, and the corresponding oxygen-functionalized materials.

The synthesized mesoporous CMK-type materials exhibit clearly differentiated textural characteristics depending on the carbon replica type (CMK-8 and CMK-9) and the subsequent oxidation treatment (Table 1). CMK-9 shows the highest specific surface area ($1210 \text{ m}^2/\text{g}$) and total pore volume ($0.96 \text{ cm}^3/\text{g}$), followed by CMK-8 ($820 \text{ m}^2/\text{g}$, $0.89 \text{ cm}^3/\text{g}$). After oxidation, both materials experience a decrease in surface area and total pore volume, with reductions ranging from 13% to 24%, depending on the case. This loss can be attributed to the incorporation of oxygen-containing groups (such as carboxylic acids, lactones, or phenols), which partially or entirely block accessible pores, particularly the smaller ones, and may also induce partial collapse or local deterioration of the porous structure.

Table 1. Textural properties obtained from Ar adsorption at 87 K for the four CMK carbon materials.

Sample	S_{BET} (m^2/g)	$V_{\mu\text{P-Ar}}$ (cm^3/g)	V_{TP} (cm^3/g)
CMK-8	820	0.10	0.89
CMK-8/O	620	0.03	0.74
CMK-9	1210	0.08	0.96
CMK-9/O	1050	0.08	0.76

The microporous volume ($V_{\mu\text{P-Ar}}$) estimated from Ar adsorption confirms these effects. In the case of CMK-8, microporosity decreases significantly upon oxidation, from 0.10 to $0.03 \text{ cm}^3/\text{g}$, indicating partial blockage or collapse of the narrow pores. For CMK-9; however, the microporous volume remains unchanged at $0.04 \text{ cm}^3/\text{g}$ before and after oxidation, indicating a lower contribution of micropores or greater structural stability toward functionalization. These differences may be linked to the inherent structural features of the two materials, where the tubular morphology of CMK-9 could favor the development of mesopores over micropores and be less affected by oxidative treatments. Additionally, variations in surface chemistry, as observed by TGA and XPS, may also contribute to these textural trends.

3.4.2. Pore Size Distribution

The pore-size distributions obtained from Ar adsorption at 87 K are shown in Figure 7a. These distributions reveal two main types of porosity: mesopores and micropores.

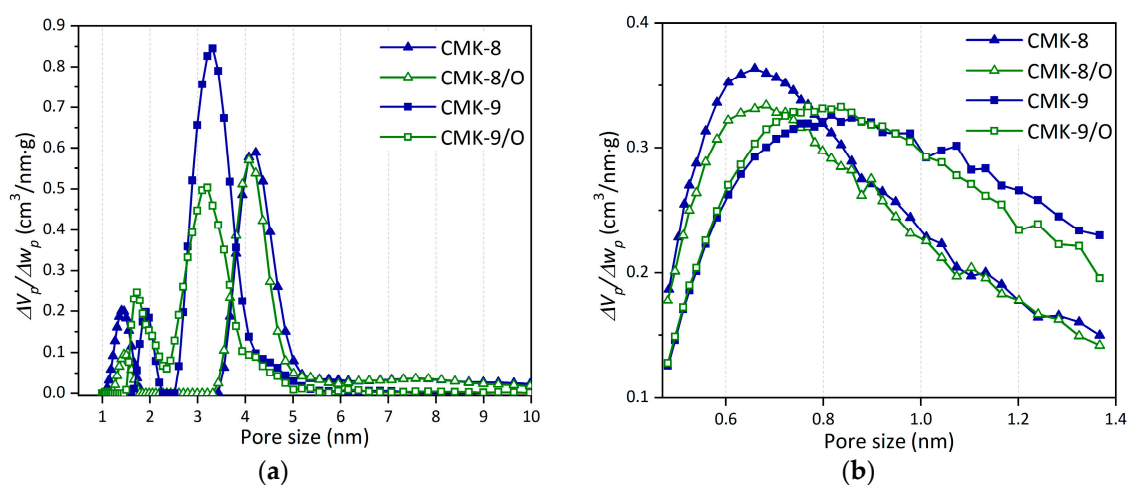


Figure 7. Pore size distributions of the four CMK samples calculated from (a) full pore size range from Ar adsorption isotherms at 87 K and (b) microporous region from CO_2 adsorption isotherms at 273 K.

The analysis of pore size distribution reveals additional structural differences. CMK-8 and CMK-9 samples exhibit different mesopore size distributions, consistent with their respective mesopore structures, which are rod-like in the case of CMK-8 and tube-like in the case of CMK-9. In CMK-9 and its oxidized derivative, the mesopores exhibit a modal size of approximately 3.2 nm, smaller than that observed in CMK-8 and CMK-8/O (4.1 nm). Regarding micropores, the modal sizes are 1.9 and 1.7 nm for CMK-9 and CMK-9/O, respectively. In contrast, for CMK-8 and CMK-8/O, they are centered around 1.5 nm, indicating that CMK-8 contains narrower micropores, which is relevant for the confinement of small molecules. In addition, this material exhibits the highest micropore volume in the series ($0.10 \text{ cm}^3/\text{g}$), which contributes to an enhanced capacity for gas capture or storage in high-energy confined spaces.

Additionally, the microporosity is more clearly observed through the pore size distributions derived from CO_2 adsorption at 273 K (Figure 7b), where CMK-9 materials exhibit slightly larger micropores compared to CMK-8, with modal micropore sizes of approximately 0.8 nm and 0.7 nm, respectively.

To adequately characterize the microporous and mesoporous domains of these carbon materials, pore size distributions were obtained using complementary approaches. Ar adsorption at 87 K was analyzed by QSDFT, which reliably describes mesopores and wider micropores; however, this adsorptive may be affected by diffusion limitations in narrow micropores ($<1 \text{ nm}$). Therefore, CO_2 adsorption at 273 K, commonly analyzed using the HK method to obtain micropore size distributions, was employed to probe narrow micropores, as the higher temperature eliminates kinetic restrictions and enables access to pores down to $\sim 0.4 \text{ nm}$ [59].

From an application standpoint, the development of microporosity is crucial for gas storage, given the higher adsorption potential in narrow pores. However, the presence of mesopores is equally essential, as it facilitates faster mass transport and improves the kinetics of adsorption–desorption cycles. Therefore, an optimal balance between both types of porosity is desirable.

3.4.3. H_2O Sorption-Desorption Isotherms

The water sorption isotherms, shown in Figure 8a,b, exhibit an S-shaped curve, classified as Type V according to IUPAC, which is typical of water sorption in hydrophobic materials such as carbon with a well-developed and ordered porosity network. All materials show a Type H1 hysteresis loop with two adsorption regions: an initial increase (up to $\sim 0.7 p/p^0$) attributed to micropore filling, followed by a second increase (up to $p/p^0 \approx 1$) associated with mesopore filling. In all cases, the well-defined hysteresis loop indicates an ordered porosity structure.

For both CMK-8 and CMK-9 materials, oxygen functionalization results in a decrease in total water adsorption. The pristine CMK-8 and CMK-9 samples exhibit a higher adsorption capacity than their oxygen-functionalized counterparts. However, in the low relative pressure region (Figure 8c), where $p/p^0 < 0.4$, and H_2O adsorption occurs primarily over functional groups [60], the trend reverses: pristine materials show the lowest adsorption. In contrast, oxygen-functionalized materials exhibit the highest adsorption at low p/p^0 . This behavior is attributed to the strong affinity of H_2O for the oxygen-containing functional groups, making these materials more hydrophilic.

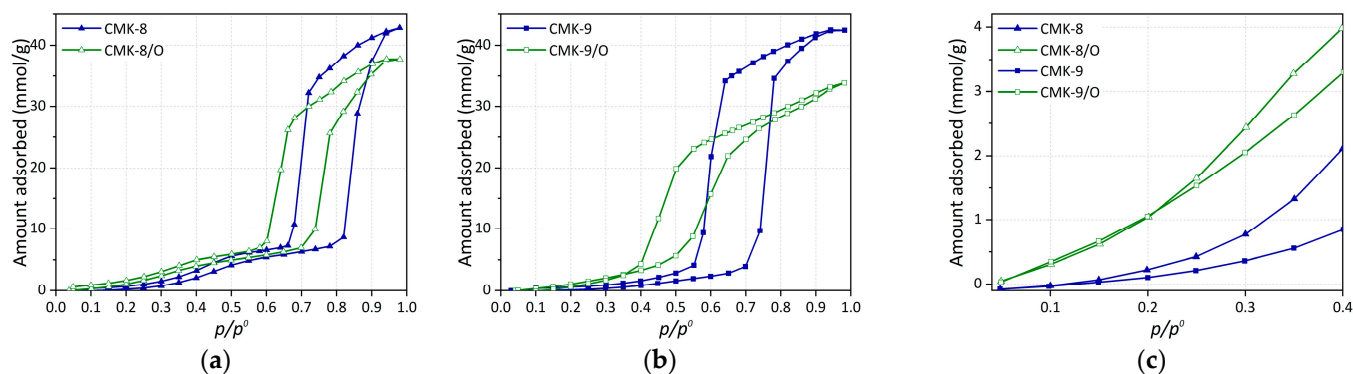


Figure 8. H₂O sorption-desorption isotherms at 298 K: (a) CMK-8 and its functionalized derivatives; (b) CMK-9 and its functionalized derivatives; (c) Low loading region ($p/p^0 < 0.4$) of H₂O sorption-desorption isotherms at 298 K.

3.5. Experimental Gas Adsorption Studies

3.5.1. CO₂ Capture

Figure 9a presents the CO₂ adsorption isotherms at 308 K and up to 10 bar for the carbonaceous materials CMK-8 and CMK-9, as well as their oxidized counterparts (CMK-8/O and CMK-9/O). All materials exhibit a characteristic behavior of micro-mesoporous solids, with a progressive increase in CO₂ uptake as pressure rises. The absence of an apparent saturation plateau suggests the coexistence of accessible micropores and unsaturated mesopores within the studied pressure range.

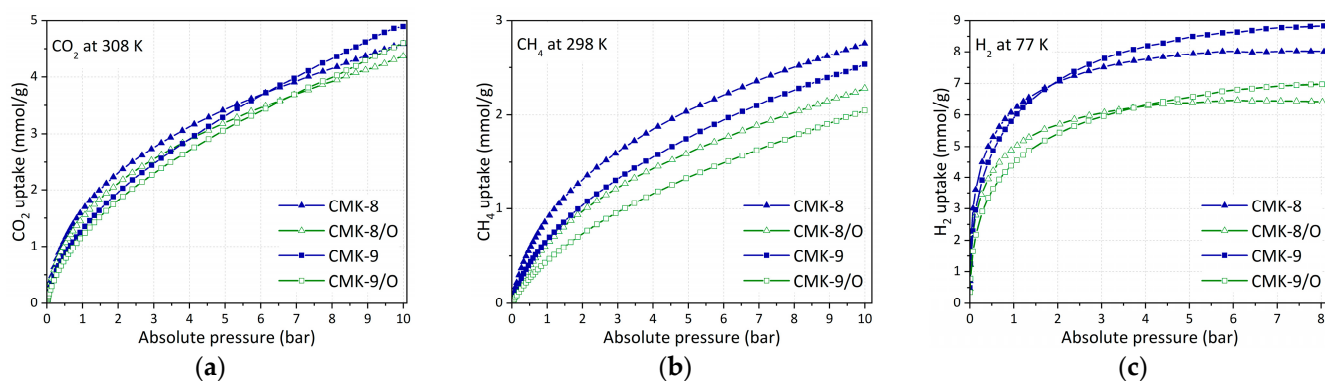


Figure 9. (a) Adsorption isotherms for all CMK-type carbon materials: (a) CO₂ at 308 K up to 10 bar, (b) CH₄ at 298 K up to 10 bar, and (c) H₂ at 77 K up to 8 bar.

As evidenced by the isotherms, CMK-8 exhibits higher CO₂ uptake than CMK-9 up to approximately 6.5 bar, beyond which the trend is reversed, and CMK-9 shows superior performance. This crossover highlights the distinct influence of textural properties under different pressure regimes. CMK-8 possesses a significantly larger micropore volume (0.10 cm³/g vs. 0.04 cm³/g for CMK-9), which enhances low-pressure adsorption due to stronger confinement effects and more intense interactions between CO₂ molecules and the pore walls. At higher pressures; however, CMK-9 benefits from a larger specific surface area (1210 m²/g) and a higher total pore volume (0.96 cm³/g), providing more accessible sites for gas accumulation.

A similar trend is observed in the oxidized materials: CMK-8/O outperforms CMK-9/O in CO₂ adsorption up to approximately 7 bar, after which CMK-9/O surpasses CMK-8/O. Oxidation leads to a general decrease in surface area and micropore volume (Table 1), resulting in somewhat lower adsorption capacities compared to their pristine counterparts. This decline in performance is likely due to the partial or complete blockage of narrower

pores or structural collapse caused by the introduction of oxygen-containing functional groups. Although these groups may enhance acid–base interactions with CO₂, their overall effect under the studied conditions appears moderately detrimental to the total uptake.

At 10 bar and 308 K, the maximum CO₂ capture reach 4.9 mmol/g for CMK-9, 4.6 mmol/g for both CMK-8 and CMK-9/O, and 4.4 mmol/g for CMK-8/O. These values are competitive within the context of carbon-based adsorbents (Table 2), clearly outperforming Maxsorb, a widely used commercial activated carbon, which reports only 2.91 mmol/g under comparable conditions (10 bar, 298 K) [61]. Nevertheless, when compared to more advanced hybrid materials such as CPO-27-Mg@KIT-6, which achieves 15.8 mmol/g at 10 bar and 298 K [62], the performance of the CMK materials remains substantially lower. This discrepancy is primarily attributed to the presence of open metal sites in Metal-Organic Frameworks (MOFs), which offer strong and specific interactions with CO₂ molecules, in contrast to the predominantly physical adsorption mechanism observed in carbon materials. Despite this limitation, CMK-8 and CMK-9, as well as their oxidized forms, offer important advantages in terms of thermal and chemical stability, as well as ease of regeneration. These attributes make them promising candidates for practical CO₂ capture technologies, particularly under moderate-pressure conditions.

Table 2. Comparison of gas adsorption performance of the studied materials and selected references.

Material	Conditions	Gas Uptake (mmol/g)	Ref
CO ₂			
* CMK-8	10 bar, 308 K	4.6	This work
* CMK-8/O	10 bar, 308 K	4.4	This work
* CMK-9	10 bar, 308 K	4.9	This work
* CMK-9/O	10 bar, 308 K	4.6	This work
CPO-27-Mg@KIT-6 (1:1)	10 bar, 298 K	15.8	[62]
Maxsorb (Activated carbon)	10 bar, 298 K	2.91	[61]
AS-2-600 (Activated carbon)	1 bar, 298 K	4.8	[9]
Coffee grounds (Activated carbon)	1 bar, 298 K	3.0	[63]
Palm date seeds (Activated carbon)	1 bar, 298 K	4.0	[9]
CH ₄			
* CMK-8	10 bar, 298 K	2.8	This work
* CMK-8/O	10 bar, 298 K	2.3	This work
* CMK-9	10 bar, 298 K	2.5	This work
* CMK-9/O	10 bar, 298 K	2.0	This work
SS-NACF	25 bar, 298 K	6.4	[2]
CBF-1273-CO ₂ -1 h	10 bar, 298 K	3.5	[64]
RHAC900-SR	35 bar, 298 K	4.3	[65]
H ₂			
* CMK-8	8 bar, 77 K	8.0	This work
* CMK-8/O	8 bar, 77 K	6.4	This work
* CMK-9	8 bar, 77 K	8.8	This work
* CMK-9/O	8 bar, 77 K	7.0	This work
SS-NACF	25 bar, 77 K	8.1	[2]
PPY2	20 bar, 77 K	2.91	[66]
PPY4800	20 bar, 77 K	4.8	[67]

* Materials studied in this work.

3.5.2. CH₄ Storage

The CH₄ adsorption isotherms at 298 K up to 10 bars for all materials are shown in Figure 9b. It can be observed that the pristine materials exhibit the highest adsorption capacity, with CMK-8 showing the best performance, reaching 2.8 mmol/g at 10 bar, and CMK-9 reaching 2.5 mmol/g (Table 2). The oxidized versions, CMK-8/O and CMK-

9/O, exhibit substantially lower performance, with rates of 2.3 mmol/g and 2.0 mmol/g, respectively. This trend is observed across the entire pressure range.

This behavior suggests that the adsorption capacity of the materials is primarily determined by their total pore volume (V_{TP}) rather than their micropore volume. Although the micropore volume increases in CMK-9 and decreases in CMK-8 after functionalization, both series show a decrease in total pore volume, which correlates with the observed reduction in CH_4 uptake. This effect is consistent with the fact that CH_4 is a neutral molecule with no permanent dipole moment. Thus, its interaction with the surface chemistry is minimal, and the main effect of functionalization is the loss of accessible pore space.

3.5.3. H_2 Storage

H_2 adsorption at 77 K follows a trend similar to that observed for CO_2 capture, though with significantly higher uptake capacities, as expected due to the cryogenic temperature employed in these experiments. As shown in Figure 9c, the pristine materials exhibit the highest hydrogen uptake, with CMK-9 being the most efficient, reaching 8.8 mmol/g at 8 bar, i.e., 1.76% w/w followed by CMK-8, which achieved 8.0 mmol/g, i.e., 1.60% w/w .

Surface oxidation leads to a notable decrease in H_2 adsorption capacity, reducing to 7.0 mmol/g for CMK-9/O and 6.4 mmol/g for CMK-8/O. This decline can be primarily attributed to the partial loss of accessible pore volume following the introduction of oxygen-containing functional groups, which reduces the number of effective sites available for physisorption. Given that H_2 is a non-polar molecule with low molecular weight, its adsorption is predominantly governed by the availability of ultramicropores (<0.7 nm) and accessible surface area at cryogenic temperatures. Therefore, any structural modification that limits access to such pores directly impacts the storage capacity.

Although this study focuses on single-component adsorption, the structure-property relationships identified allow us to anticipate the behavior of CMK-type carbons under multicomponent conditions. The higher micropore volume and narrower micropores of CMK-8 suggest a preferential uptake of CO_2 in competitive environments, particularly at low pressures where confinement effects and the strong quadrupolar moment of CO_2 dominate adsorption. In contrast, the larger micropores and mesopores of CMK-9, together with its higher accessible surface area, are expected to favor greater uptake at intermediate and high pressures for weakly interacting gases such as CH_4 and H_2 , where adsorption is primarily governed by accessible pore volume rather than pore size.

The results also show that oxidative or amine functionalization does not enhance the adsorption performance of CMK-type carbons toward CO_2 , CH_4 , or H_2 . Unlike functionalized silica materials, where chemisorption or specific acid-base interactions can markedly increase CO_2 uptake, adsorption in CMK-derived carbons is dominated by dispersion forces and confinement effects. Consequently, surface groups do not improve adsorption and may even reduce capacity by partially occupying internal pore space. These observations highlight that optimization strategies for CMK-based adsorbents should focus on tailoring the balance between narrow micropores, which enhance low-pressure CO_2 adsorption, and larger micropores or mesopores, which become increasingly relevant for CH_4 and H_2 storage at higher pressures.

3.6. Experimental Isothermic Enthalpy of CO_2 , CH_4 , and H_2 Adsorption

The isothermic heat of adsorption ($\Delta_{Ads}h$) profiles of CO_2 , CH_4 , and H_2 on CMK-8 and CMK-9, along with their oxidized derivatives (CMK-8/O and CMK-9/O), provide insight into the interplay between surface chemistry and textural features.

For CO_2 (Figure 10a), the oxidized materials exhibit enhanced initial $\Delta_{Ads}h$ values, reaching 31 kJ/mol for CMK-8/O and 34 kJ/mol for CMK-9/O, compared to 31 kJ/mol

and 29 kJ/mol for the pristine CMK-8 and CMK-9, respectively. While CMK-8 and CMK-8/O share similar initial values, the increase observed in CMK-9/O suggests stronger interactions due to the presence of oxygen-containing functional groups (e.g., carboxylic acids and hydroxyls), which increase the surface polarity and promote specific interactions with the CO₂ quadrupole. In all cases, $\Delta_{Ads} \dot{h}$ decreases with increasing adsorption loading (n_{Ads}), reflecting the progressive occupation of high-energy adsorption sites. This trend is more pronounced in the oxidized materials, likely due to their greater surface heterogeneity and the distribution of functionalized sites.

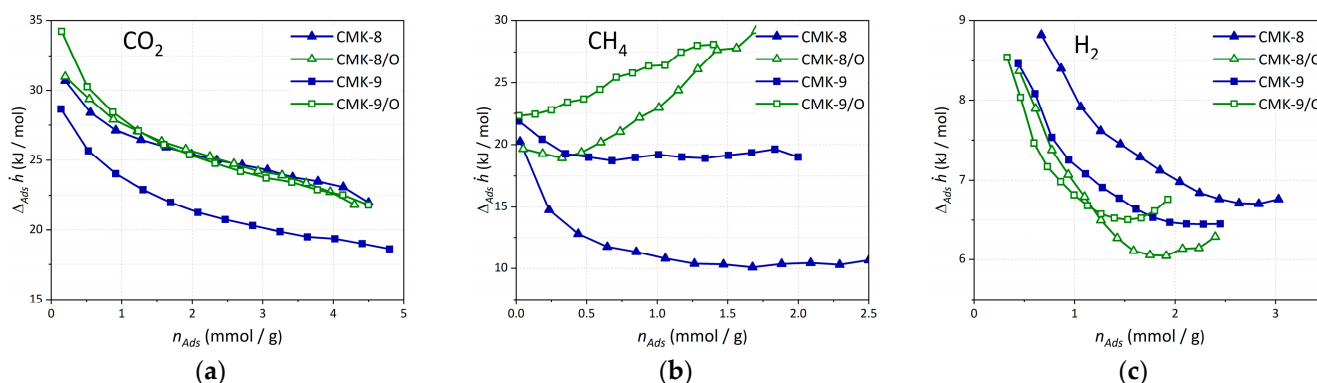


Figure 10. Experimental isosteric heat of adsorption as a function of loading for (a) CO₂, (b) CH₄, and (c) H₂ on all CMK-type carbon materials.

In the case of CH₄ (Figure 10b), a non-polar molecule, the $\Delta_{Ads} \dot{h}$ values are significantly lower, ranging from ~10 to 30 kJ/mol. The pristine CMK-8 exhibits the weakest interactions (~10–12 kJ/mol), consistent with its wider mesopores (4.1 nm) and limited surface functionality. Upon oxidation, both CMK-8/O and CMK-9/O show a marked increase in $\Delta_{Ads} \dot{h}$ at higher loadings, with values rising above 25–30 kJ/mol. This trend is not solely attributable to stronger adsorbent-adsorbate interactions, but rather reflects a combination of factors: the onset of adsorbate-adsorbate interactions within confined mesopores as adsorption progresses, and the enhancement of dispersive interactions promoted by oxygenated surface groups. These functional groups can increase the carbon surface's polarizability, thereby enhancing van der Waals interactions with CH₄ molecules. The smaller mesopore diameter of CMK-9 (3.2 nm vs. 4.1 nm in CMK-8) likely enhances this effect by promoting closer proximity between CH₄ molecules, creating a more favorable environment for retention, particularly in the oxidized form.

For H₂, adsorption (Figure 10c) occurs through weak physisorption mechanisms, as reflected in the low $\Delta_{Ads} \dot{h}$ values (~6–9 kJ/mol). Nevertheless, CMK-8 consistently shows slightly higher $\Delta_{Ads} \dot{h}$ across the loading range compared to CMK-9, particularly in its pristine form. This can be attributed to its narrower micropores (1.5 nm modal size) and higher micropore volume (0.10 cm³/g), which enhance confinement effects critical for H₂ storage at cryogenic temperatures. In contrast, the oxidized materials display slightly reduced $\Delta_{Ads} \dot{h}$ values. This decrease may be explained by partial blockage of micropores due to the incorporation of oxygen-containing functional groups, which can obstruct access to the narrowest and highest-energy adsorption sites. As a result, the overall adsorption potential within micropores is reduced, leading to lower isosteric heat values than in the pristine materials.

3.7. Computational Gas Adsorption Studies

3.7.1. Gas Capture

Figure 11 shows excess adsorption isotherms for CH_4 , CO_2 , and H_2 for monodispersed slit-shaped pores of type GP and GOx, with pore widths $H = 8, 10, 12, 15, 20$, and $30 \text{ \AA}$ within the pressure range $0 \leq P \leq 10 \text{ bar}$ (extended isotherms up to 60 bar are provided in the Figures S2–S4, Tables S1–S6). Narrower pores exhibit significantly higher uptake at low pressures due to overlapping interaction potentials from opposing pore walls, while larger pores show increased adsorption at elevated pressures.

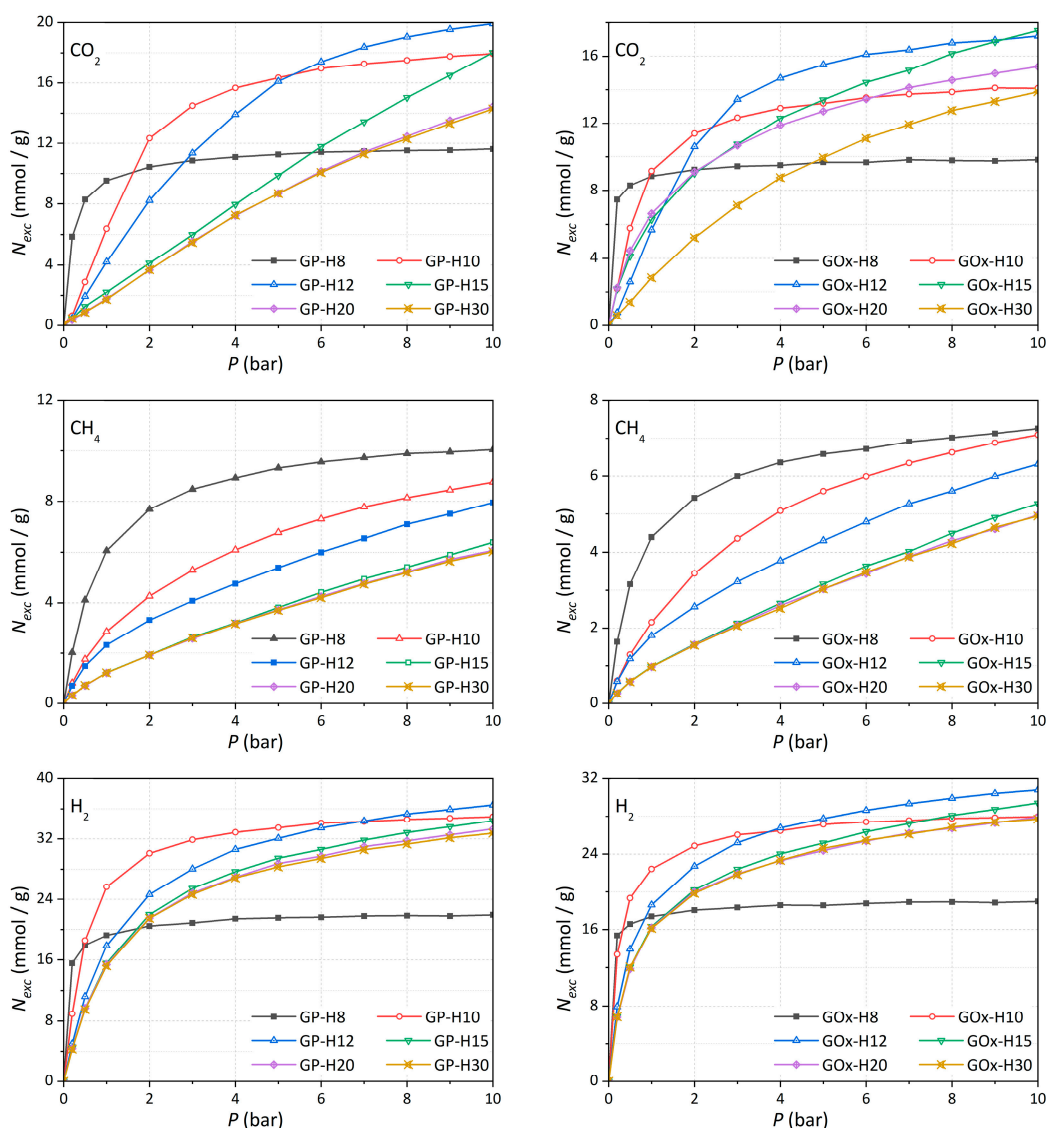


Figure 11. Adsorption isotherms for CO_2 (top), CH_4 (center), and H_2 , (bottom) in GP-H (left column) and GOx-H (right column) for $H = 8, 10, 12, 15, 20$, and $30 \text{ \AA}$.

We examine the influence of polar functional groups (hydroxyl and epoxy) by comparing adsorption in GP-H (pristine graphene) and GOx-H (oxidized graphene) pores across pore sizes categorized as small ($8 \text{ \AA}$), medium ($10\text{--}15 \text{ \AA}$), and large ($\geq 20 \text{ \AA}$). Figure 12 compares adsorption isotherms for CH_4 , CO_2 , and H_2 at representative pore widths of 8, 12, and $30 \text{ \AA}$.

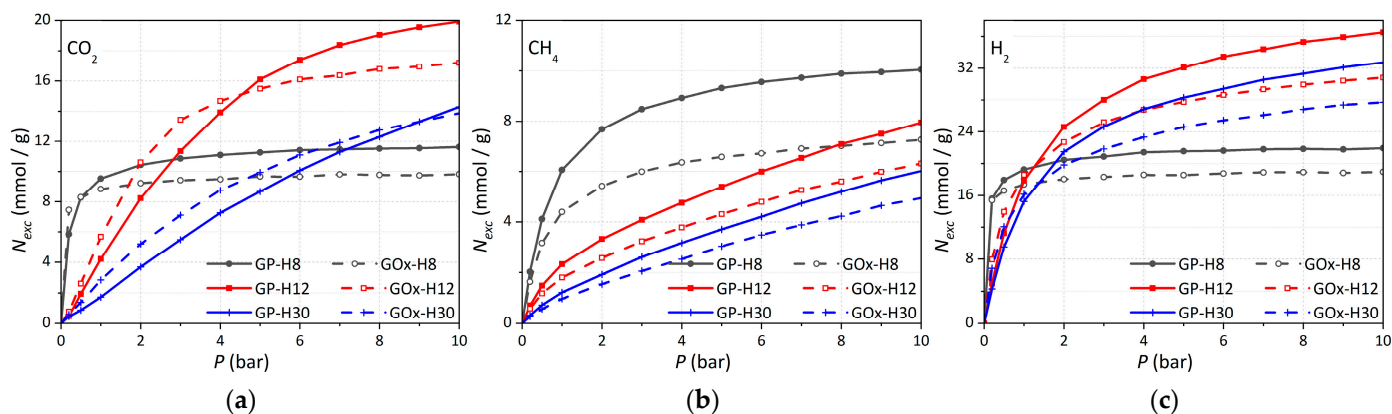


Figure 12. Comparison of CO₂ (a), CH₄ (b), and H₂ (c) adsorption in GP (pristine) and GOx (oxidized) pores of 8 Å, 12 Å, and 30 Å widths. Figures S5–S7 shows comparisons for additional pore widths.

Key observations include: (i) for CH₄, the presence of functional groups consistently reduces uptake, particularly in narrower pores, due primarily to steric volume occupied by surface groups (Figure 1). (ii) H₂ shows a similar, though less pronounced, reduction in uptake; its smaller molecular size allows easier access between functional groups, mitigating the impact. (iii) for CO₂, polar groups enhance adsorption at low pressures by increasing affinity via interactions between the significant electric quadrupole moment of CO₂ and the dipole of hydroxyl groups. At higher pressures; however, the occupied pore volume from the functional groups reduces overall capacity.

3.7.2. Comparison with Experimental Adsorption Isotherms

To relate these simulations to experimental data (Figure 9), we account for the actual pore-size distributions (PSDs) of the materials (Figure 7). Following Ortiz et al. [37], PSDs are modeled as sums of Gaussian distributions

$$\text{PSD}(H) = \sum_{H_0} a_{H_0} e^{-\frac{(H-H_0)^2}{\sigma_{H_0}^2}}. \quad (4)$$

The area under each Gaussian, Z_{H_0} , corresponds to the volume fraction of pores centered at H_0 . The normalized pore fraction f_{H_0} is computed as:

$$f_{H_0} = \frac{\frac{Z_{H_0}}{H_0}}{\sum_{H_0} \frac{Z_{H_0}}{H_0}} \quad (5)$$

Synthetic adsorption isotherms $N(P)$ are then constructed as weighted sums [37]:

$$N(P) = \alpha \sum_{H_0'} f_{H_0'} N_{H_0'}(P) \quad (6)$$

where $N_{H_0'}(P)$ are isotherms for individual pore widths, and α scales for differences in surface area between the experimental material and the model (approximately 2600 m²/g). Figure 13 compares synthetic and experimental isotherms for CMK-8, CMK-8/O, CMK-9, and CMK-9/O. Notably, the PSDs from subcritical nitrogen adsorption are applied directly to supercritical adsorption of CH₄, CO₂, and H₂ without further adjustment/fit.

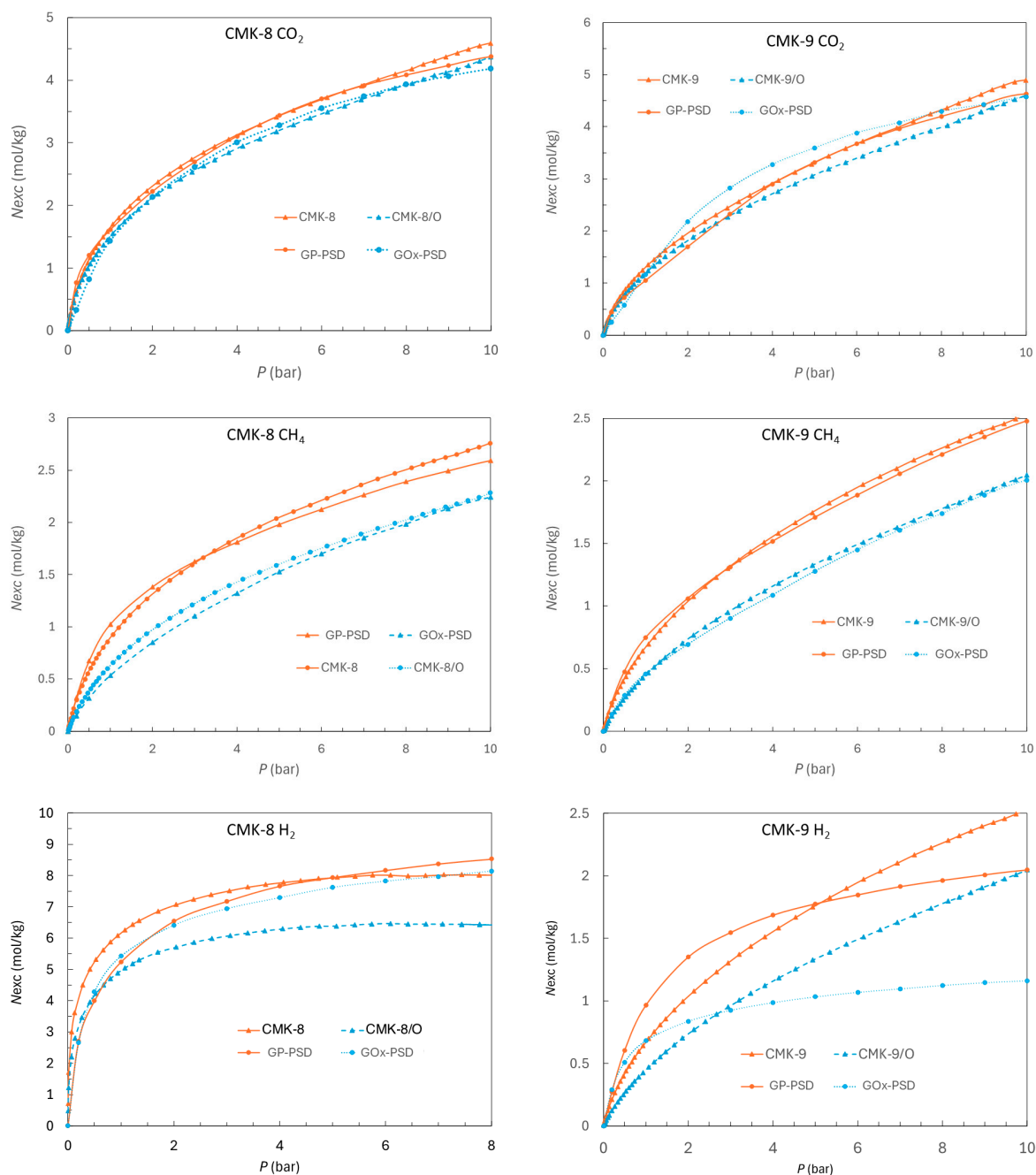


Figure 13. Synthetic (Equation (6)) vs. experimental excess adsorption isotherms for CMK materials. **Left panels:** CMK-8 and CMK-8/O. **Right panels:** CMK-9 and CMK-9/O. **CO₂ (top), CH₄ (middle), H₂ (bottom).**

Given the simplifying assumptions of the synthetic isotherm model—including slit-pore geometry, the coarse-grained Gaussian representation of the N₂-derived PSDs, and the neglect of pore connectivity, curvature, and possible pore-blocking effects by oxygen functional groups—the comparison in Figure 13 is intended to be qualitative rather than quantitative. Pristine CMK-8 and CMK-9 carbons are commonly described as gyroid-derived twisted-rod and twisted-tube architectures, respectively, with highly interconnected and curved pore networks [5], features that are not represented in slit-pore models. These topological differences, which may be further altered upon functionalization, are expected to have only a limited impact on CH₄ and CO₂ adsorption trends but become critical for H₂ adsorption, which is highly sensitive to subtle confinement effects, pore connectivity, and

surface topology. Consequently, while the model reproduces the general adsorption trends for CH₄ and CO₂ reasonably well, the agreement for H₂ is substantially poorer, reflecting the intrinsic limitations of simplified pore geometries for describing hydrogen adsorption in complex carbon frameworks.

3.7.3. Isostatic Enthalpy of CO₂, CH₄, and H₂ Adsorption

Simulated isosteric heats of adsorption $\Delta_{Ads} \bar{h}$ are presented in Figure 14 for small (8 Å), medium (12 Å), and large (30 Å) pores in both GP and GOx models. Narrower pores generally yield higher adsorption enthalpies. While the simulated enthalpy ranges qualitatively align with experimental values (Figure 10), a quantitative comparison would require a careful synthesis of weighted enthalpies across PSDs, as described in Ortiz et al. [37].

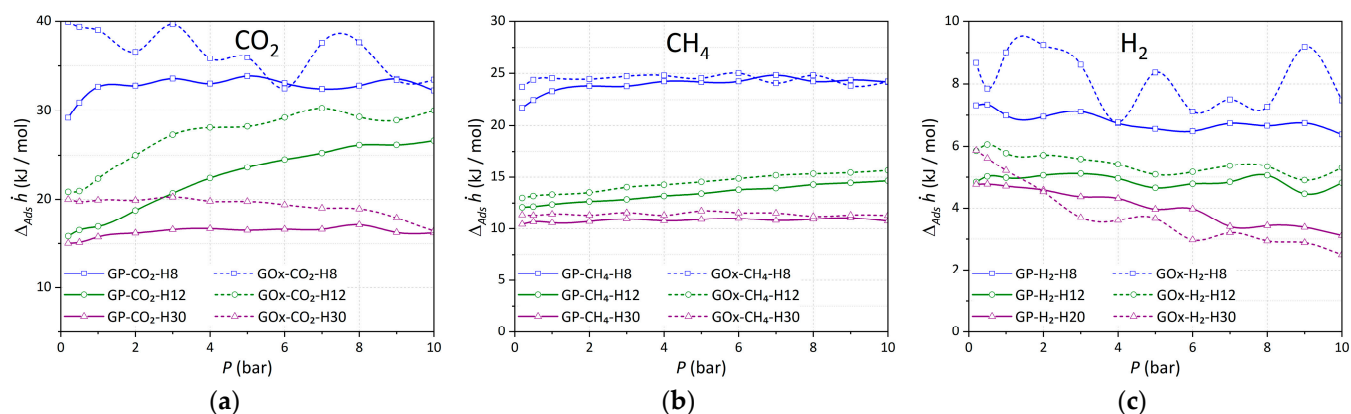


Figure 14. Simulated isosteric enthalpy profiles for (a) CO₂, (b) CH₄, and (c) H₂ adsorption for pristine (GP) and oxidized (GOx) structures for small ($H = 8$ Å), medium (12 Å), and large (30 Å) pores.

Oxidized pores (GOx) show consistently elevated enthalpies for CO₂ adsorption, reflecting enhanced interactions due to oxygen-containing surface groups that increase polarity. Differences for CH₄ and H₂ between oxidized and pristine surfaces are minimal, consistent with their non-polar nature.

3.7.4. Mechanism for Enhanced Interactions of CO₂ with Oxidized Materials

To elucidate the origin of CO₂ affinity for oxidized pores, radial distribution functions $g(r)$ between adsorbate molecules and adsorbent atoms were calculated [21–23,68]. Figure 15 shows $g(r)$ between hydroxyl oxygen atoms and the centers of mass of CH₄, CO₂, and H₂. A pronounced correlation peak is observed for CO₂, indicating strong attraction to hydroxyl groups, whereas correlations for CH₄ and H₂ are weaker. Reducing OH group density or gas pressure increases this correlation by minimizing interference and adsorbate crowding. Using an uncharged atomic approximation (UAA) for H₂, which omits the quadrupole moment, slightly lowers correlation. Other surface atoms, such as epoxy oxygens or graphene carbons, showed no notable correlation peaks (see Figures S8 and S9). This enhanced CO₂–OH interaction via electrostatic complementarity explains the increased low-pressure uptake in oxidized pores.

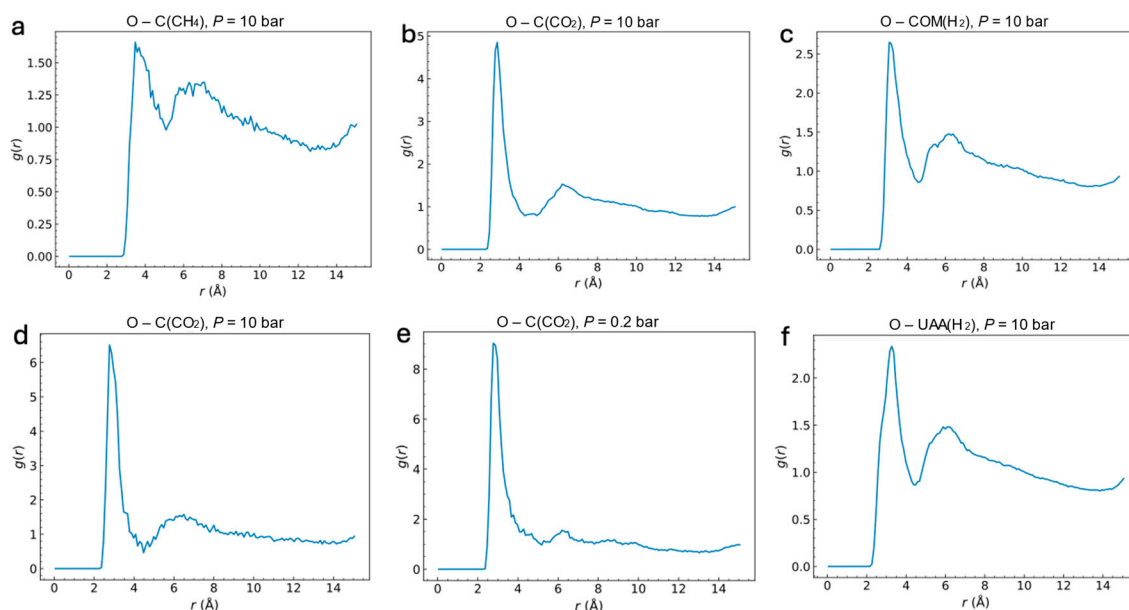


Figure 15. Pair correlation function $g(r)$ between the hydroxyl oxygens in GP-H2O with the CH_4 (a), CO_2 (b), and H_2 (c) molecules computed at 10 bar. Panel (d) shows an oxidized pore with a single OH group attached, emphasizing the strong correlation it generates. Panel (e) represents a low-pressure run (0.2 bar). Panel (f) corresponds to a UAA model of H_2 , i.e., without an electric quadrupole, resulting in slightly reduced correlation.

4. Conclusions

This study presents a comprehensive investigation that combines experimental techniques and molecular simulations to elucidate how the porous structure and surface functionalization via HNO_3 oxidation distinctly influence the adsorption behavior of key gases— CO_2 , CH_4 , and H_2 —on ordered mesoporous carbons CMK-8 and CMK-9.

CMK-8, characterized by a notably higher micropore volume ($0.10 \text{ cm}^3/\text{g}$ vs. $0.04 \text{ cm}^3/\text{g}$ for CMK-9), demonstrated superior CO_2 and H_2 adsorption capacities at low pressures, alongside significant CH_4 uptake across the pressure range studied. These findings highlight the critical role of micropore confinement and specific adsorbate-surface interactions in narrow pores, which enhance adsorption potential, especially for gases with intense quadrupole moments or requiring high-energy adsorption sites. In contrast, CMK-9's larger specific surface area ($1210 \text{ m}^2/\text{g}$) and greater total pore volume ($0.96 \text{ cm}^3/\text{g}$) enabled enhanced adsorption performance at elevated pressures, particularly for CO_2 and H_2 , underscoring the importance of mesopore accessibility and pore volume in facilitating progressive gas uptake under moderate to high-pressure regimes.

Surface oxidation with HNO_3 introduced oxygen-containing functional groups, including phenols, carbonyls, and carboxyls, substantially modifying surface chemistry. XPS analysis confirmed the incorporation of these groups, evidenced by new components in the C 1s and O 1s spectra, revealing a higher degree of chemical heterogeneity in CMK-9/O compared to CMK-8/O.

The increased surface polarity strengthened adsorbate interactions, as evidenced by elevated isosteric heats of adsorption for CO_2 . However, this chemical enhancement was accompanied by a reduction in accessible surface area and pore volume, resulting in lower maximum adsorption capacities for all gases studied. This trade-off between enhanced chemical affinity and diminished structural accessibility highlights a key challenge in adsorbent design: optimizing functionalization to improve selectivity and binding strength without excessively compromising pore availability.

The strong agreement between experimental adsorption isotherms and the qualitative agreement of adsorption isosteric heats validate the structural and chemical models employed and reinforce the reliability of the combined characterization approach. Molecular simulations provided mechanistic insight into gas-surface interactions, including the enhanced CO₂ affinity for hydroxyl groups via electrostatic quadrupole-dipole interactions and the steric hindrance effects of surface groups on CH₄ and H₂ uptake. This synergy of experimental and computational approaches enables a rational framework for tailoring pore architecture and surface chemistry to target specific gases and operating conditions.

Overall, this work demonstrates that an effective strategy for gas capture and storage must strike a careful balance between pore system accessibility and surface chemical functionality. Given their thermal stability, chemical robustness, and regenerability, CMK-8 and CMK-9, along with their oxidized derivatives, are promising materials for the sustainable storage and separation of CO₂, CH₄, and H₂ at moderate pressures and temperatures. Future work could fine-tune oxidation levels and pore structures to optimize selectivity and capacity further, and extend these insights to hybrid and composite materials for enhanced performance in industrial applications.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/cleantechnol8010019/s1>, Figure S1. Adsorption isotherms of (a) CO₂ (273 and 308 K), (b) CH₄ (298 and 313 K), and (c) H₂ (77, 90, and 105 K). Figure S2. Large pressure adsorption isotherms for CH₄ in GP-H and GOx-H for $H = 8, 10, 12, 15, 20$, and $30 \text{ \AA}$. Figure S3. Large pressure adsorption isotherms for CO₂ in GP-H and GOx-H for $H = 8, 10, 12, 15, 20$, and $30 \text{ \AA}$. Figure S4. Large pressure adsorption isotherms for H₂ in GP-H and GOx-H for $H = 8, 10, 12, 15, 20$, and $30 \text{ \AA}$. Figure S5. Comparison of CH₄ adsorption isotherms for original (GP) and oxidized (GOx) structures. Figure S6. Comparison of CO₂ adsorption isotherms for original (GP) and oxidized (GOx) structures. Figure S7. Comparison of H₂ adsorption isotherms for original (GP) and oxidized (GOx) structures. Figure S8. Comparison of pair correlation function $g(r)$ between the graphene carbons in GP-H20 (left) or GOx-H20 (right), for of CH₄ (top) and CO₂ (bottom). Virtually no major correlation is found, and no variation exists between the two adsorbates or adsorbents. Figure S9. Pair correlation function $g(r)$ between the epoxy oxygens in GP-H20 (left) or GOx-H20 (right), for of CH₄ (top) and CO₂ (bottom). There is a small correlation but no significant variation exists between the two adsorbates or adsorbents. Table S1. Excess Adsorption Isotherms CH₄ (300 K) on GP structures. Table S2. Excess Adsorption Isotherms CH₄ (300 K) on GOx structures. Table S3. Excess adsorption isotherms CO₂ (300 K) on GP structures. Table S4. Excess adsorption isotherms CO₂ (300 K) on GOx structures. Table S5. Excess Adsorption Isotherms H₂ (77 K) on GP structures. Table S6. Excess Adsorption Isotherms H₂ (77 K) on GOx structures.

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