

Porous carbon-based materials for electrochemical CO₂ capture by supercapacitive swing adsorption

Jiaxin Li^{1,†}✉ and Fei Li¹

¹ ARC Centre of Excellence for Carbon Science and Innovation, School of Chemical Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia

[†] Present address: Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge CB2 1EW, United Kingdom

Carbon Future 2026, 3, 9200091 <https://doi.org/10.26599/CF.2026.9200091>

Received: August 29, 2026; Revised: September 16, 2026; Accepted: September 21, 2026

✉ Address correspondence to Jiaxin Li (jiaxin.li0321@gmail.com)

ABSTRACT: Electrochemical supercapacitive swing adsorption (SSA) is an emerging CO₂ capture technology that couples reversible charge storage with electrically driven CO₂ uptake and release, offering the potential for low-energy operation. Porous carbon electrodes are central to SSA because they govern charge storage, ion adsorption and transport, and interfacial CO₂ enrichment, thereby determining capture performance. However, the relationships between carbon structure, interfacial electrochemistry, and CO₂-capture mechanisms remain poorly understood. This Review provides a carbon-centered perspective on SSA. We first summarize the fundamentals of SSA, including cell configurations, electrode materials, and proposed capture mechanisms. Particular emphasis is placed on the evolution of carbon electrodes from commercial porous carbons to tailored porous carbons, quinone-functionalized carbons, and covalent-organic-framework-based composites. We then discuss emerging structure–performance relationships, focusing on how surface area, pore architecture, and surface chemistry influence CO₂ capture capacity, kinetics, and energy consumption, and derive empirical design principles for SSA electrodes. Finally, we highlight key challenges and opportunities in mechanistic understanding, material and device design, evaluation under realistic conditions, integration of CO₂ capture with utilization, and techno-economic analysis and life-cycle assessment. By linking carbon structure to interfacial processes and device-level performance, this Review provides a framework for the rational design of scalable SSA systems for electrochemical carbon capture.

KEYWORDS: Supercapacitive swing adsorption; electrochemical CO₂ capture; porous carbon; supercapacitors

1 Introduction

Anthropogenic CO₂ emissions from fossil-fuel use, industrial processes, and large-scale deforestation have driven the rapid increase in atmospheric CO₂ concentrations and global warming¹. Without effective mitigation, CO₂ emissions on the order of tens of gigatonnes are expected to push global warming beyond 2 °C by mid-century, leading to severe societal and ecological consequences such as heat-related mortality, intensified droughts and floods, and biodiversity loss¹. Limiting further warming requires deep reductions in greenhouse-gas emissions together with effective carbon-management strategies. Carbon capture, storage, and utilization remain among the most scalable approaches for reducing emissions from concentrated industrial sources, including power plants, cement production, steel manufacturing, and the chemical industry, while also supporting negative-emission pathways when coupled with biomass conversion or direct air capture.

However, current capture technologies remain energy-intensive. Amine scrubbing, the dominant industrial approach, uses aqueous amine solutions to absorb CO₂ from gas streams chemically. Although this technology is mature and highly selective, it suffers from high solvent-regeneration energy demand, solvent volatility, oxidative/thermal degradation, equipment corrosion, and potential secondary environmental concerns associated with degraded amine products. Regeneration typically requires energy of 2–4 GJ·ton^{−1} CO₂, corresponding to 90–180 kJ·mol^{−1} CO₂, in addition to 0.3–0.5

MWh·ton^{−1} CO₂ of electrical energy for CO₂ compression and auxiliary operation^{2,3}. Solid adsorbents such as CaO, functionalized silicas, activated carbons, and porous polymers avoid some solvent-related issues, but their regeneration commonly relies on temperature, pressure, or vacuum swings and can still require substantial energy input (Fig. 1a), for example, 7–12 GJ·ton^{−1} CO₂ for limestone-based systems^{2,4,5}. These limitations motivate electrically driven capture processes that can enable reversible CO₂ uptake and release under milder conditions.

Electrochemical CO₂ capture has emerged as a promising route because it can potentially operate under mild conditions and couple directly with renewable electricity. Recent reviews broadly classify these systems into several major families, including pH/ion-swing, redox-mediated, and capacitive processes^{6–8}. In pH- or ion-swing systems, electrochemical reactions alter alkalinity or ionic composition to shift CO₂/HCO₃[−]/CO₃^{2−} equilibria^{9,10}, whereas redox-mediated systems rely on redox-active species or materials whose CO₂ affinity changes upon reduction or oxidation^{11,12} (Fig. 1b, c). Although these approaches have advanced rapidly, they often require careful management of electrolyte crossover, mediator stability, membrane selectivity, or parasitic Faradaic reactions. Supercapacitive swing adsorption (SSA) provides an alternative capacitive strategy (Fig. 1d), in which charging/discharging porous electrodes drives electric double-layer formation and ion redistribution, enabling reversible CO₂ uptake and release. As SSA primarily relies on capacitive rather than Faradaic charge storage, it retains several attractive

advantages of supercapacitors, including the use of abundant carbon materials, simple cell configuration and operation, rapid electrical response, high reversibility, and good cycling stability.

Carbon materials are attractive for SSA because their porosity and surface chemistry are highly tunable, while their chemical robustness, relatively low cost, and mature electrode-processing methods facilitate practical implementation. Importantly, carbon electrodes are not merely passive conductive scaffolds but active interfaces that regulate charge storage and ion transport while shaping CO₂ dissolution, local pH, and carbonate equilibria. These interfacial processes collectively determine key SSA metrics, including CO₂ capture capacity, kinetics, energy consumption, and cycling stability. Conventional supercapacitor design rules therefore cannot be transferred directly to SSA. For example, high surface area or capacitance alone does not necessarily translate into high CO₂ uptake or low energy consumption. Instead, SSA performance reflects the combined effects of carbon structure (*e.g.*, surface area, pore structure, surface chemistry), electrolyte composition, electrode architecture (*e.g.*, thickness, binder structure and

distribution, and gas/liquid diffusion pathway), and operating conditions (*e.g.*, gas compositions, flow rate, charging protocol).

Several recent reviews have summarized electrochemical CO₂ capture, including SSA, with emphasis on device configurations, operating mechanisms, and system-level performance^{5-8,13-15}. However, how carbon structure governs SSA performance remains comparatively underexplored. In this review, we therefore focus on the role of carbon properties in SSA mechanisms and performance, rather than providing another broad overview of electrochemical CO₂ capture technologies. We trace the development from commercial porous carbons to tailored porous carbons and redox-functionalized electrodes, identify emerging structure–performance relationships (SPRs) affecting capture capacity, kinetics, and energy consumption, and derive empirical design principles for future SSA electrodes. By placing carbon materials at the center of SSA design, this Review aims to bridge fundamental interfacial understanding with the development of scalable and application-relevant electrochemical CO₂ capture systems.

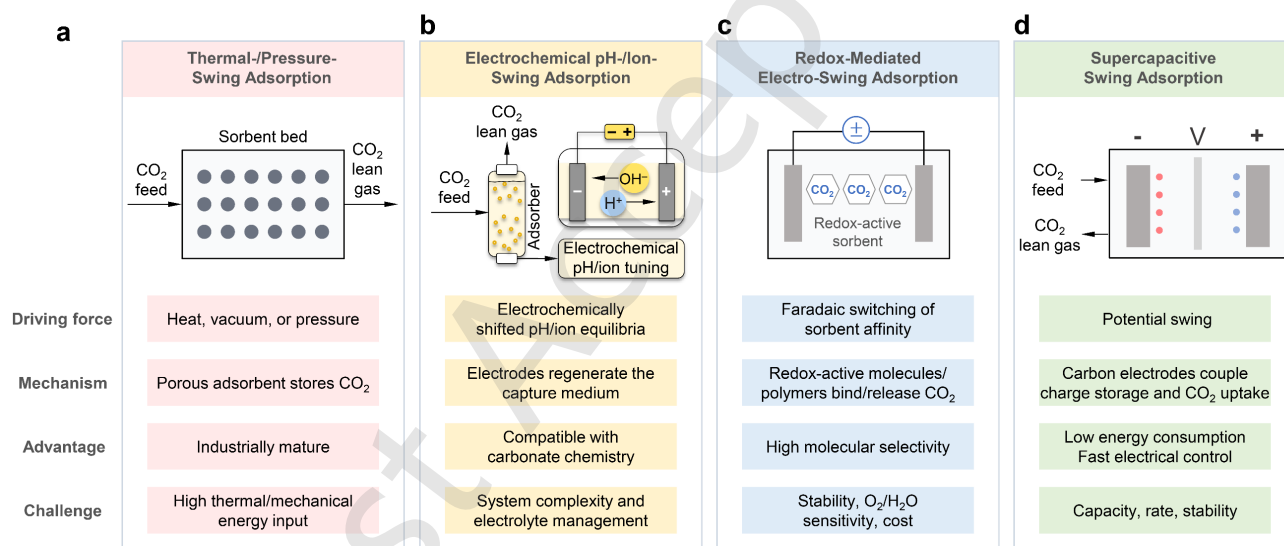


Fig. 1 Comparison of conventional adsorption and electrochemically driven CO₂ capture technologies. **a**, Thermal- and pressure-, and vacuum swing adsorption based on regeneration of porous adsorbents by temperature, vacuum, or pressure changes. **b**, Electrochemical pH-/ion-swing adsorption based on voltage-induced modulation of carbonate equilibria through pH and ion-balance shifts. **c**, Redox-mediated electro-swing adsorption based on reversible changes in the CO₂ affinity of redox-active sorbents. **d**, Supercapacitive swing adsorption based on low-voltage electric-double-layer charging of porous carbon electrodes for reversible CO₂ uptake and release.

2 Fundamentals of SSA

2.1 Origin and concept of SSA

The concept of SSA was first introduced by Landskron and co-workers in 2014¹⁶. SSA is an emerging electrochemical CO₂-capture technology that typically uses porous carbon electrodes and aqueous electrolytes to reversibly capture and release CO₂ under a small applied voltage. Unlike thermally driven capture processes, SSA can operate near ambient conditions and offers the potential for low-energy regeneration, rapid electrical

response, and long cycling stability based on predominantly capacitive charge storage.

2.2 Basic and advanced cell configurations

A typical SSA device consists of porous electrodes, an aqueous electrolyte, and a CO₂-containing gas phase within an electrochemical cell. At least one electrode is exposed to gas while remaining in contact with the electrolyte. During charging, electric double layers form within electrolyte-filled carbon pores, redistributing ions near the carbon/electrolyte interface and altering the local chemical environment for CO₂

uptake, while discharging or reverse charging reverses these changes and promotes CO₂ release. SSA therefore operates through the interplay of charge storage and interfacial CO₂ chemistry, rather than by simple adsorption on dry carbon. In practical operation, the charging protocol can be tailored to regulate CO₂ uptake and release using variable-voltage, constant-voltage, and combined charging–holding modes.¹⁷ Beyond the variable-voltage cycling commonly used in supercapacitor characterization, such flexibility allows the electrochemical protocol to be optimized specifically for CO₂ capture. Most reported SSA systems employ aqueous electrolytes, enabling operation at relatively low voltages while offering additional advantages in safety and sustainability.

SSA cell configurations have evolved from simple symmetric static cells toward asymmetric, flow-based, and stacked architectures. Early systems commonly used symmetric configurations with identical porous carbon electrodes (Fig. 2a).

More recently, asymmetric cells, in which the structure and/or mass loading of the two electrodes are independently adjusted, have been introduced to better balance charge storage and enhance net CO₂ capture by suppressing CO₂ release from the counter electrode (Fig. 2b)¹⁷. Flow-through and stacked configurations have also been explored to improve mass transport, electrode utilization, and scalability.

SSA performance should be evaluated using metrics that reflect both intrinsic material properties and device-level effects. Common metrics include gravimetric CO₂ capture capacity, capture rate, energy consumption, charge or energy efficiency, and cycling stability. Because these metrics depend strongly on cell configurations, gas compositions, charging protocols, electrode loadings, and normalization basis, direct comparison across studies requires consistent reporting of experimental conditions and calculation methods.

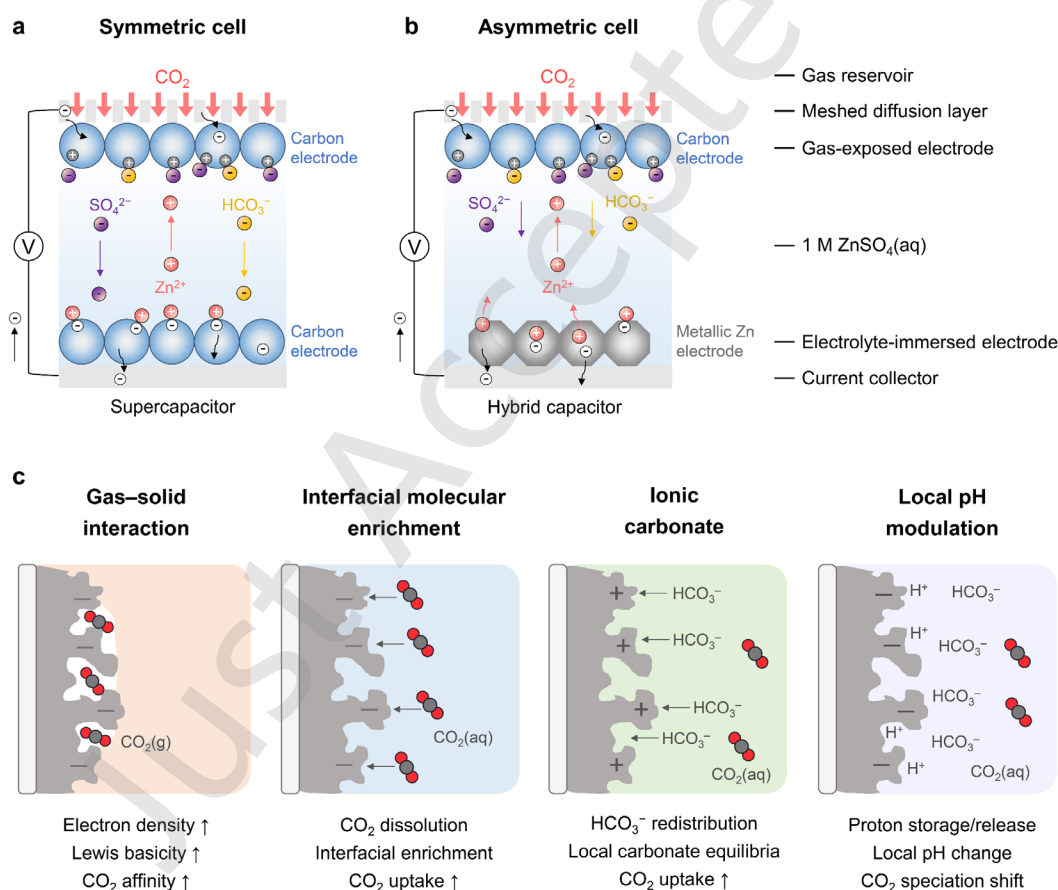


Fig. 2 Cell configurations and proposed mechanisms of supercapacitive swing adsorption for electrochemical CO₂ capture. **a, b,** Schematics of electrochemical CO₂ capture in symmetric supercapacitors and asymmetric Zn-ion hybrid capacitors. Adapted from Ref. ¹⁷. © 2025 The Authors, licensed under a Creative Commons Attribution 4.0 International License. **c,** Proposed mechanisms, including gas-solid interaction, interfacial molecular enrichment, ionic carbonate, and local pH modulation.

2.3 Proposed mechanisms

The molecular mechanism of SSA remains under debate. Experimentally, CO₂ uptake/release are reproducibly coupled to electrode charging/discharging, while the magnitude and kinetics of the response depend strongly on electrode materials, electrolyte compositions, and operating conditions. However, these observations do not establish a clear molecular pathway.

Several complementary mechanisms have been proposed to explain electrochemically driven CO₂ uptake/release (Fig. 2c)^{5,13–15}. In the **gas–solid interaction mechanism**, negative charging is proposed to increase the electron density and Lewis basicity of the carbon surface, thereby strengthening its affinity for Lewis-acidic CO₂ molecules^{5,13,15,16}. This mechanism requires at least part of the pore network to remain accessible

to the gas phase. As many charge-storing pores are electrolyte-filled, direct gas–solid adsorption is more likely to occur in partially wetted or gas-accessible regions, and its overall contribution remains uncertain¹⁵. In the **interfacial molecular enrichment mechanism**, CO₂ first dissolves in the electrolyte and is then proposed to become locally enriched within electrolyte-filled pores near the charged carbon/electrolyte interface. Such enrichment could arise from differences in CO₂ solubility between the interfacial and bulk electrolyte environments, together with interfacial electric fields and confinement effects. In the **ionic carbonate mechanism**, electrochemical polarization is proposed to redistribute ionic inorganic carbon species, particularly HCO₃[−], within the electric double layer. This redistribution can shift local carbonate equilibria and thereby contribute to electrochemically driven CO₂ uptake and release^{5,13–15}. The contribution of this pathway relative to molecular CO₂ enrichment is likely to be system-dependent. A related **local pH modulation mechanism** proposes that proton storage and release occur at the carbon/electrolyte interface during electrode polarization. The resulting changes in local proton activity and pH can alter CO₂ speciation, thereby coupling electrode charging/discharging to CO₂ uptake/release^{14,15}. These mechanisms are not necessarily mutually exclusive and may operate simultaneously, with their relative contributions depending on carbon structure, electrolyte composition, cell configuration, and operating protocols. Distinguishing among them will require more direct operando measurements of interfacial pH, CO₂ speciation within the pores, and changes in local CO₂ concentration during uptake and release.

The mechanisms discussed above are primarily based on conventional porous carbon electrodes without specific CO₂-binding functionalities. Introducing new electrode chemistries or redox-active functional groups could therefore open additional capture pathways. For example, quinone-functionalized carbons and covalent organic frameworks (COFs) can couple capacitive charge storage with redox-mediated CO₂ binding, in which changes in the oxidation state of specific sites directly regulate their affinity for CO₂.

3 Carbon-based materials for SSA

Carbon electrodes are central to SSA because CO₂ capture occurs within porous carbon/electrolyte interfaces during electrochemical charging. At the material level, **pore structure** determines the accessible interface and transport pathway. **Surface chemistry** regulates wetting and pore accessibility, while modifying interfacial ion distributions, local acid–base equilibria, and interactions with CO₂-derived species, thereby affecting capture capacity, rate, reversibility, and cycling stability. At the electrode level, **electrode architecture**, including thickness, loading, and gas/liquid-transport pathways, determines how effectively these intrinsic material properties can be utilized under practical operating conditions. Accordingly, the development of carbon electrodes for **capacitive SSA** has progressed from commercial porous carbons to structurally tailored porous carbons, alongside increasingly diverse electrode and cell architectures. We additionally discuss quinone-functionalized carbons and COF-based composites as related extensions of this materials

platform, in which redox-active sites introduce hybrid capacitive–redox or redox-dominated CO₂-capture pathways beyond conventional SSA.

Table 1 provides an overview of reported SSA performance. Here, we note that direct performance comparison between studies should be made with caution because of differences in cell configurations, gas compositions, and operating protocols.

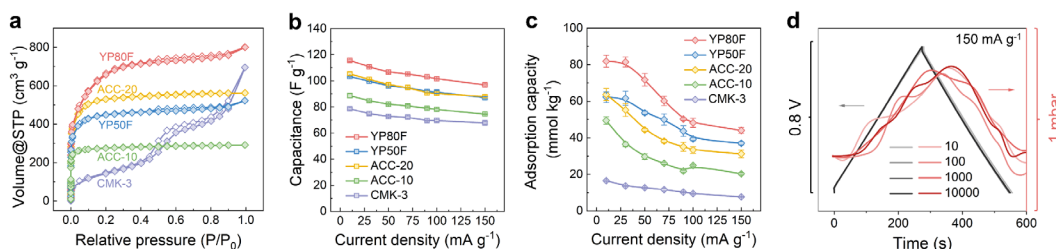
3.1 Commercial porous carbons

Commercial porous carbons have provided the experimental basis for SSA because they are readily available, electrically conductive, inexpensive, and compatible with conventional electrode fabrication. Although they were not designed specifically for electrochemical CO₂ capture, BPL 4×6, YP-50F, YP-80F, activated carbon cloths, CMK-3, Supersorb, and Acticarb-type carbons have been used as model electrodes to establish SSA principles and to identify how pore structure, electrolyte composition, cell configuration, and charging protocol influence capture performance^{16–27}. Many of these carbons are classical capacitive materials that have been widely used as benchmark electrodes in supercapacitors and capacitive deionization²⁸.

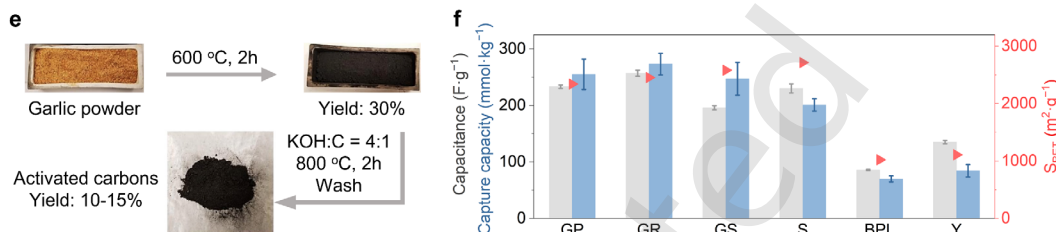
BPL 4×6 was used in the earliest demonstrations of SSA and subsequently became a benchmark carbon for mechanistic and device studies. This bituminous-coal-derived activated carbon has a predominantly microporous structure, a specific surface area determined by Brunauer–Emmett–Teller method (S_{BET}) of 640 m²·g^{−1} reported in early SSA studies and good chemical robustness. Using BPL electrodes in aqueous NaCl electrolytes, the Landskron group first demonstrated reversible CO₂ uptake and release driven by low-voltage charging/discharging, with an early static cell delivering a CO₂ capacity of 40 mmol·kg^{−1}¹⁶. BPL was subsequently used in flow-through and radial-flow modules, giving capacities of 38–63 mmol·kg^{−1}, depending on gas-flow design, electrode area, current density, voltage window, and holding protocol^{20,21}. BPL was also used to clarify electrolyte effects. By changing electrolyte concentration and composition, the Landskron group showed that electrolyte composition strongly affects SSA capacity, charge efficiency, and energy consumption^{22,23}. Although the capture capacities of BPL are not very high, these studies established BPL as an important model system and showed that SSA cannot be understood solely as conventional dry-carbon physisorption but instead involves electrochemical charge storage and electrolyte-mediated interfacial processes.

Comparisons with other commercial carbons further revealed that surface area alone does not determine SSA performance and that carbon texture and electrode architecture are also important. Under the same radial-flow conditions, BPL and carbide-derived Y carbon delivered relatively low capacities of 70 and 84.5 mmol·kg^{−1}, respectively, whereas **coke-derived Supersorb** reached 201 mmol·kg^{−1}²⁹. In parallel, Sun *et al.* used commercial **Acticarb PS1000F** supported on gas-diffusion layers and paired with a cation-exchange membrane to achieve much higher flow-cell capacities of up to 893 mmol·kg^{−1} through improved gas transport and membrane-enabled control of a locally alkaline environment near the electrode surface³⁰.

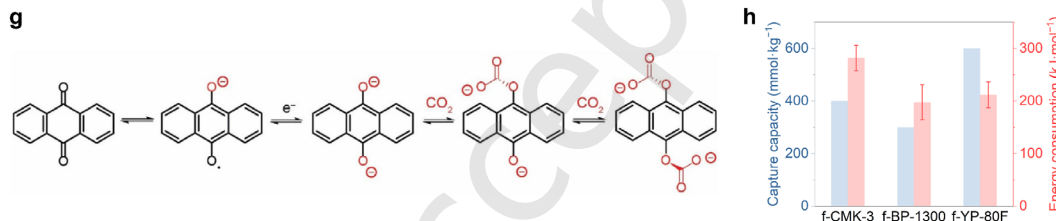
Commercial Porous Carbons



Tailored Porous Carbons



Quinone-Functionalized Carbons



COF/CNT Composites

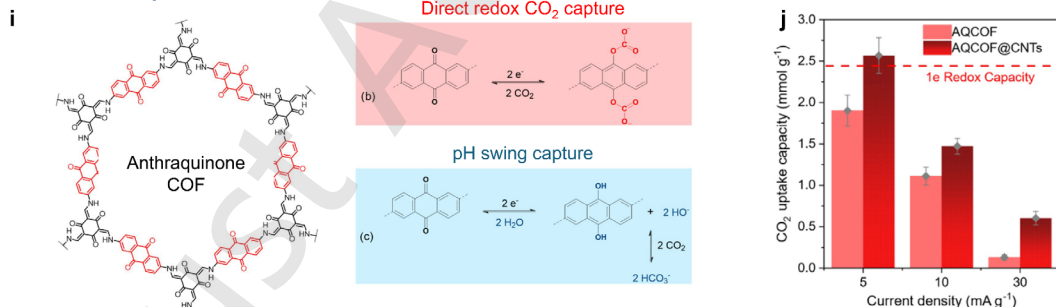


Fig. 3 Evolution of carbon-based electrodes for supercapacitive swing adsorption, including commercial porous carbons, tailored porous carbons, quinone-functionalized carbons, and COF/CNT composite electrodes. a, N₂ sorption isotherms at 77 K of YP-50F, YP-80F, CMK-3, ACC-10, and ACC-20. **b**, Discharge capacitances and **c**, CO₂ capture capacities at different current densities. **d**, Cycling stability of YP-80F under CO₂. **e**, Scheme of the preparation process. **f**, S_{BET}, capacitance, and CO₂ capture capacities of garlic-derived activated carbons and commercial carbons. **g**, Proposed redox-capture mechanism of anthraquinone-functionalized carbon electrodes. **h**, CO₂ capture capacity and energy consumption of quinone-functionalized carbons. **i**, Proposed capture pathways of anthraquinone-based COF electrodes and **j**, CO₂ uptake capacities of AQCOF and AQCOF@CNTs. **Figs. a–d** adapted from Ref. ²⁷. © The Author(s) 2024, licensed under a Creative Commons Attribution 4.0 International License. **Fig. e** adapted from Ref. ²⁹, © 2023 The Authors, licensed under a Creative Commons Attribution 4.0 International License. **Fig. g** adapted from Ref. ³¹, © 2024 The Author(s), licensed under a Creative Commons Attribution 4.0 International License. Data in **Figs. f** and **h** were extracted from Refs. ²⁹ and ³¹, respectively, and replotted by the authors. **Figs. i, j** adapted from Ref. ³², © 2025 The Authors, licensed under a Creative Commons Attribution 4.0 International License.

High-surface-area microporous carbons and carbon cloths have also been used to clarify the roles of surface area and pore accessibility in SSA. Kuraray YP-50F and YP-80F are high-surface-area microporous activated carbons with S_{BET} of 1,700

and 2,300 m²·g⁻¹, respectively, and relatively low oxygen contents. Activated carbon cloths (ACC-10 and ACC-20) provide different architectures by combining macroscopic fibrous transport pathways with internal microporosity, with

S_{BET} values of 1,000 and 2,000 $\text{m}^2\cdot\text{g}^{-1}$ (Fig. 3a), whereas CMK-3 offers an ordered mesoporous framework but a substantially lower S_{BET} of 350 $\text{m}^2\cdot\text{g}^{-1}$. When evaluated as supercapacitor electrodes, these carbons exhibited capacitances of 78 to 116 $\text{F}\cdot\text{g}^{-1}$ at 10 $\text{mA}\cdot\text{g}^{-1}$ and 68 to 97 $\text{F}\cdot\text{g}^{-1}$ at 150 $\text{mA}\cdot\text{g}^{-1}$ (Fig. 3b). Under the same pure- CO_2 static-cell conditions, their SSA capacities broadly follow electrochemical capacitance and accessible surface area. At 10 $\text{mA}\cdot\text{g}^{-1}$, capacities ranged from 17 $\text{mmol}\cdot\text{kg}^{-1}$ for CMK-3 to 82 $\text{mmol}\cdot\text{kg}^{-1}$ for YP-80F, whereas at 150 $\text{mA}\cdot\text{g}^{-1}$ they decreased to 8–44 $\text{mmol}\cdot\text{kg}^{-1}$ (Fig. 3c). YP-80F also showed good cycling stability over 10,000 cycles at 150 $\text{mA}\cdot\text{g}^{-1}$ (Fig. 3d). These results indicate that accessible microporosity contributes strongly to SSA capacity, whereas ordered mesoporosity alone does not compensate for low surface area and capacitance. The loss of capacity at higher current densities further indicates increasing transport limitations within the porous electrode. Together, this model-carbon series helped distinguish the contribution of micropores to charge-storage capacity from that of larger transport pathways to rate performance^{17,19,24,27}. More importantly, nuclear magnetic resonance (NMR) studies using these carbons revealed high concentrations of dissolved CO_2 within electrolyte-filled carbon pores relative to the bulk electrolyte, supporting the idea that nanopore confinement can modify local CO_2 solvation and concentration²⁵. This observation provides an important link between carbon pore structure and the molecular environment relevant to electrochemical CO_2 capture.

Overall, commercial porous carbons have established both a material benchmark and a mechanistic starting point for SSA. Beyond serving as benchmark electrodes, they have helped reveal how electrochemically accessible surface area, electrolyte composition, and cell architecture influence electrochemical CO_2 capture. These insights provide the basis for moving from commercial carbons toward tailored carbons with optimized pore structures, surface chemistry, and electrode architectures that maintain accessibility under practical operating conditions.

3.2 Tailored porous carbons

Tailored porous carbons aim to overcome the structural limitations of commercial carbons for SSA. Although commercial carbons are useful benchmark electrodes, they were not originally designed to optimize electrochemically accessible surface area, ion/ CO_2 transport, and interfacial chemistry for CO_2 capture. Based on insights gained from commercial porous carbons, recent work has begun to rationally tailor pore architecture and surface chemistry specifically for SSA. The key challenge is to provide sufficient electrochemically accessible surface area and connected transport pathways without compromising electronic conductivity and structural stability.

Garlic-derived activated carbons from the Landskron group represent an early biomass-based strategy for improving SSA electrodes²⁹. In the initial study, garlic powder, roots, and skin were carbonized and subsequently KOH-activated to produce GP-AC, GR-AC, and GS-AC with high S_{BET} of 2,341, 2,454, and 2,582 $\text{m}^2\cdot\text{g}^{-1}$, respectively (Fig. 3e). Their SSA performance, however, did not correlate directly with surface area, highlighting the importance of pore structure and other electrode-level properties. Despite having the highest S_{BET} , GS-AC showed higher resistance and energy consumption, whereas

GP-AC benefited from its higher electrode density and therefore higher volumetric capture performance. GR-AC provided the most balanced combination of properties, with a high S_{BET} , a pore volume of 1.41 $\text{cm}^3\cdot\text{g}^{-1}$, and a micro/mesoporous structure, delivering a CO_2 capacity of 273 $\text{mmol}\cdot\text{kg}^{-1}$ and a capture rate of 301 $\text{mmol}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$, substantially outperforming BPL carbon under the same testing conditions (Fig. 3f).

Building on this material-level screening, GR-AC was subsequently translated into high-loading electrodes for practical flow-based operations³³. The 1 mm-thick hot-pressed electrodes, with a loading of 38 $\text{mg}\cdot\text{cm}^{-2}$, achieved capacities of 312 $\text{mmol}\cdot\text{kg}^{-1}$ at -1.0 V and 524 $\text{mmol}\cdot\text{kg}^{-1}$ at -1.4 V with stable cycling over 130 h. This platform was further extended to concentrated MgBr_2 and MgCl_2 electrolytes and O_2 -containing gas feeds, reaching CO_2 capacities of up to 780 $\text{mmol}\cdot\text{kg}^{-1}$ ³⁴. Together, these studies illustrate a progression from material screening to high-loading electrodes and more application-relevant operating conditions. However, broader implementation of biomass-derived activated carbons will require improved control over precursor variability, synthesis yields, and the environmental impact of large-scale chemical activation.

A more deliberately designed porous carbon was reported by the Forse group using 2,4,6-triaminopyrimidine (TAP) as precursor and $\text{MgCl}_2\cdot 6\text{H}_2\text{O}$ as porogen during high-temperature carbonization¹⁸. **TAP-1000**, prepared at 1,000 °C, showed the best balance of microporosity and mesoporosity, with an S_{BET} of 2,830 $\text{m}^2\cdot\text{g}^{-1}$, a total pore volume of 2.73 $\text{cm}^3\cdot\text{g}^{-1}$, and 2.4 at% nitrogen. Compared with YP-80F, TAP-1000 retained micropores near 0.9 nm while introducing substantially more mesoporosity, providing a pore network favorable for both charge storage and mass transport. Under the same gas-cell protocol, TAP-1000 achieved a maximum adsorption rate of 2,083 $\text{mmol}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$, compared with 349 $\text{mmol}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ for YP-80F, while maintaining energy consumption below 10 $\text{kJ}\cdot\text{mol}^{-1}$ under pure CO_2 testing¹⁸. These results highlight the importance of combining microporous surface area with mesoporous transport pathways for high-rate SSA, rather than maximizing either pore regime alone.

Beyond pore architecture, surface chemistry represents another important design variable. This effect has been examined using oxygen-functionalized YP-80F²⁷. Hydrogen peroxide oxidation increased oxygen content and hydrophilicity while largely preserving S_{BET} and pore structure. Despite exhibiting higher capacitance, the oxidized carbons showed lower CO_2 capture capacities than pristine YP-80F. This result demonstrates that increasing surface functionality, wettability, or capacitance does not necessarily translate into improved SSA performance. Instead, the chemical identity and interfacial role of surface groups appear to be more important than their overall abundance.

Taken together, these studies show that rational carbon design for SSA requires optimization across multiple structural parameters. Pore accessibility, transport, and surface chemistry must be co-optimized and retained at practical electrode loadings.

3.3 Quinone-functionalized carbons

CO_2 capture in conventional non-redox-functionalized carbons is primarily associated with electric-double-layer charging, ion

redistribution, and changes in interfacial carbonate equilibria. Quinone functionalization introduces redox-active CO₂-binding sites into conductive porous carbon electrodes. Quinones, particularly anthraquinones, undergo reversible electrochemical reduction to form more nucleophilic reduced states that can bind CO₂, followed by CO₂ release upon oxidation (Fig. 3g). This redox-dependent CO₂ binding is mechanistically analogous to redox-mediated electrochemical

CO₂ capture using molecular quinones or other redox-active sorbents. In quinone-functionalized porous carbons, however, this Faradaic contribution coexists with capacitive charge storage by the carbon framework, giving rise to a hybrid capacitive-redox system. Immobilizing quinones on carbon supports can suppress dissolution and crossover of redox-active species while retaining the conductivity, porosity, and processability of the carbon electrodes.

Table 1. Summary of reported electrode materials, cell configurations, and CO₂ capture performance of supercapacitive swing adsorption and related redox-mediated capture systems.

Material class	Cells	Electrodes Gas-exposed electrodes	Counter electrodes	S _{BET} (m ² ·g ⁻¹)	V _{Pore} (cm ³ ·g ⁻¹)	O (at %)	Electrolytes	Gas composition	Capture capacity (mmol·kg ⁻¹)	Capture rate (mmol·kg ⁻¹ ·h ⁻¹)	Energy efficiency (%)	Energy consumption (kJ·mol ⁻¹)	Refs
Commercial porous carbons	Static cell	BPL		640	/	/	1 M NaCl(aq)	15% CO ₂ 85% N ₂	40	/	74	103.6	16
	Flow cell						1 M NaCl(aq)		38	/	/	57	20
	Scaled-up flow cell						1 M NaCl(aq)		24–63	32–119	83.4	117–386	21
	Radial-flow cell						Deionized H ₂ O/ 0.01/0.1/1/3 /5 M NaCl(aq)		32.8–63.2	58.7–87.5	4.5–78.8	97–712	22
	Radial-flow cell						LiCl/NaCl/KCl/ MgCl ₂ /NaF/NaBr/NaHCO ₃ / Na ₂ SO ₄ (aq)		28.7–67.3	37.1–87.5	60.3–78.0	90–237	23
	Flow cell	Bipolar electrode	Stacks	1023	/	/	1 M NaCl(aq)	15% CO ₂ 85% N ₂	55.2–61.3	132–137	67.3–84.4	60.2–142.2	35
	Static cell	YP-50F		1690	/	6.5	1 M NaCl(aq)	Pure CO ₂	50–112	43–96	/	356–751	24
		YP-50F		1690	/		1 M Na ₂ SO ₄ (aq)		60–150	/	/	/	36
		YP-80F	Zn	2324	/	5.14	1 M ZnSO ₄ (aq)		74–208	/	/	51	17
		YP-80F	ACC	2324	/	5.14	1 M Na ₂ SO ₄ (aq)		114	/	/	/	
		YP-80F		2324	/	5.14	1 M Na ₂ SO ₄ (aq)		81.9	350	/	/	27
		ACC-10		1094	/	6.40	Na ₂ SO ₄ (aq)		49.4	/	/	/	
		ACC-20		2004	/	6.34			63.7	/	/	/	
		CMK-3		353	/	3.41			16.5	/	/	/	
		O-YP-80F-1		2216	/	7.88			76.3	/	/	/	
		O-YP-80F-7		2243	/	8.13			53.2	/	/	/	
		YP-80F		2324	/	5.14	1 M Na ₂ SO ₄ at pH 1.1/7.0/13.4 1 M NaOH/ NaHCO ₃ (aq)			80–240	/	/	19
	Flow cell	Acticarb PS1000F		964.7	0.67	9.8	3 M NaCl(aq)	10%/20% CO ₂ humidified simulated flue gas	186–813 196–893	331–933 361–1281	/	35–349 32–207	30
Tailored porous carbons	Radial-flow cell	Garlic powder-AC		2341	1.11	18.7	1 M NaHCO ₃ (aq)	15% CO ₂	255	268	49.6	177	29
		Garlic roots-AC		2454	1.41	6.3		85% N ₂	273	301	54.2	179	
		Garlic skin-AC		2582	1.31	3.3			247	267	16.7	371	
		Coke-derived Supersorb Y carbon		2715	1.31	23.9			201	206	52.8	204	
		Garlic root-AC		1109	0.60	3.4			84.5	106	54.1	304	
	Flow cell	Garlic root-AC		1464	0.75		1 M NaHCO ₃ (aq)		312–485	167–225	/	72–311	33
	Radial flow cell	Garlic roots AC		/	/	/	3 M MgCl ₂ (aq)	15% CO ₂ 5% O ₂ 80% N ₂	780	/	/	220	34
	Static cell	TAP-1000		2830	/	/	1 M Na ₂ SO ₄ (aq)	Pure CO ₂	149	2083	/	<10	18
Quinone-functionalized carbons	Static cell	f-CMK-3	YP-80F	/	/	9.3	[Bmim][TFSI]	Pure CO ₂ ; 15% CO ₂ / 85% N ₂	400	386	/	281.6	31
		f-BP-1300		/	/	14.4			300	386	/	197.4	
		f-YP-80F		/	/	9.7			600	477	/	211.5	
		f-CMK-3	YP-80F	/	/	/			200–400; 1000	/	/	254–256; 830	37
COFs	Static cell	AQCOF@CNTs	Activated carbon	325	/	/	[Bmim][TFSI]	Pure CO ₂	>2600	/	/	/	32

Note: Table 1 provides an overview of reported SSA performance. However, direct comparisons between studies should be made with caution because of differences in electrode materials, electrolyte composition, cell configurations, and operating conditions. In addition, maximum performance metrics within an individual study may also have been obtained under different conditions and should not be interpreted as simultaneously achieved values.

An early demonstration of quinone-functionalized porous carbon electrodes for electrochemical CO₂ capture was reported by the Forse group, who showed that covalently immobilized anthraquinone can enable reversible redox-driven CO₂ capture in porous carbons^{31,37}. The mesoporous CMK-3 scaffold was selected to facilitate quinone grafting while maintaining electrolyte and CO₂ accessibility within the porous electrode. Quinone grafting reduced the accessible surface area and pore volume, indicating partial occupation or blockage of the carbon pores. The resulting anthraquinone-functionalized CMK-3 (f-CMK-3) displayed clear redox activity and CO₂-dependent pressure changes that followed reduction/oxidation cycles, supporting a substantial contribution from quinone redox chemistry to reversible CO₂ uptake and release. Under an optimized operating voltage window, f-CMK-3 delivered a CO₂ capacity of 0.4 mmol·g⁻¹ with an energy consumption of 256 kJ·mol⁻¹. Expanding the voltage window increased the initial capacity to 1.0 mmol·g⁻¹ but also increased energy consumption to 830 kJ·mol⁻¹ and accelerated capacity decay³⁷.

The parent carbon structure strongly affects quinone loading, redox-site accessibility, and cycling stability. A subsequent comparative study examined anthraquinone-functionalized CMK-3, BP-1300, and YP-80F. Among the three materials, the initial CO₂ capacities followed the order f-YP-80F (0.6 mmol·g⁻¹) > f-CMK-3 (0.4 mmol·g⁻¹) > f-BP-1300 (0.3 mmol·g⁻¹) (Fig. 3h)³¹. Although f-CMK-3 had the highest quinone loading, f-YP-80F showed the best overall performance, including higher utilization of grafted quinone (>50%), lower energy consumption than f-CMK-3, and better cycling stability. After 200 cycles, f-YP-80F retained 50% of its CO₂ capacity, decreasing from 0.6 to 0.3 mmol·g⁻¹, whereas f-CMK-3 retained 40% and f-BP-1300 showed only minimal adsorption. The corresponding energy consumptions were 211.5 kJ·mol⁻¹ for f-YP-80F, 281.6 kJ·mol⁻¹ for f-CMK-3, and 197.4 kJ·mol⁻¹ for f-BP-1300.

These studies show that quinone loading alone does not determine capture performance; the accessibility, electrochemical utilization, and stability of redox-active sites are equally important. Quinone-functionalized carbons bridge capacitive and redox-mediated CO₂ capture, but grafting adds synthetic complexity and can reduce pore accessibility. Incomplete site utilization lowers charge-to-CO₂ efficiency and can increase energy consumption, while degradation or irreversible reactions compromise cycling stability. Future development should therefore improve redox-site utilization and stability, while minimizing pore blockage, synthetic complexity, and energy demand.

3.4 COF and COF/CNT composites

Quinone-based COFs provide a more structurally defined alternative to quinone-grafted carbons by integrating anthraquinone units into periodic porous frameworks, thereby providing well-defined redox sites and more controlled site accessibility. As CO₂ uptake and release are governed primarily by quinone reduction and re-oxidation, these materials are better regarded as redox-dominated electrochemical CO₂-capture systems rather than conventional SSA, although capacitive charge storage may coexist.

An anthraquinone-based COF (AQCOF) demonstrates reversible electrochemical CO₂ uptake through quinone reduction during negative charging, and subsequent CO₂

release upon oxidation (Fig. 3i)³². As pristine COFs have limited electronic conductivity, carbon nanotubes (CNTs) were incorporated to improve charge transport and electrochemical utilization of redox sites. AQCOF@CNTs containing 7 wt% CNTs retained a similar S_{BET} of 325 m²·g⁻¹ to pristine AQCOF (310 m²·g⁻¹), increasing CO₂ uptake from 1.5 to 2.6 mmol·g⁻¹ in an ionic-liquid electrolyte (Fig. 3j). However, this uptake decreased markedly at higher current densities, reflecting kinetic limitations associated with ion/CO₂ transport and accessibility of redox sites. Long-term cycling in the ionic-liquid electrolyte also showed severe capacity decay, with only ~20% of the initial uptake retained after 300 cycles.

Switching from the ionic-liquid electrolyte to aqueous Na₂SO₄ electrolyte improved rate capability, energy efficiency, and cycling stability, while introducing additional contributions from local pH swing effects alongside quinone redox chemistry. At 100 mA·g⁻¹, AQCOF@CNTs delivered a CO₂ uptake of 0.8 mmol·g⁻¹ with an energy consumption of 37 kJ·mol⁻¹. Removing the voltage-hold step reduced the energy consumption to 31 kJ·mol⁻¹, and further optimization of the cycling protocol lowered it to 28 kJ·mol⁻¹. The aqueous system remained stable for 500 cycles. However, O₂ tolerance remains limited, with CO₂ uptake decreasing to 0.34 mmol·g⁻¹ in the presence of 15% O₂.

Overall, quinone-based COF/CNT composites combine molecularly defined redox-active CO₂-binding sites with conductive porous frameworks and can achieve higher CO₂ uptake than quinone-grafted porous carbons. Their main limitations include limited electronic conductivity and mass transport, together with oxygen sensitivity and cycling instability under demanding operating conditions. Future work should focus on improving conductivity, O₂ tolerance, and long-term electrode stability while preserving pore accessibility.

4 Structure-performance relationships

4.1 Specific surface area

S_{BET} is an important starting descriptor for SSA carbons, but it does not alone predict CO₂ capture performance. According to the classical electric double-layer capacitor (EDLC) model, capacitance generally increases with electrochemically accessible surface area. S_{BET} can therefore provide a useful first descriptor of the available porous surface, although the N₂-accessible surface measured by BET analysis does not necessarily correspond to the surface accessible to solvated electrolyte ions under SSA conditions. Larger accessible surface areas can provide more interfacial sites for charge storage and CO₂ capture. As summarized in Fig. 4a, several material series tested under comparable conditions show a positive relationship between S_{BET} and CO₂ capture capacity. For example, YP-80F outperformed lower-surface-area carbons under the same gas-cell protocol²⁷, and garlic-derived activated carbons showed much higher capacities than BPL²⁹. However, carbons with comparable S_{BET} can perform quite differently, and the material with the highest surface area does not necessarily deliver the highest capacity. This indicates that SSA performance depends not only on total surface area but also on its electrochemical accessibility, pore-size distribution, wettability, and transport within the porous electrode.

The relationship between S_{BET} and capture rate is weaker (Fig. 4b). High surface area can increase charge-storage capacity, but

rapid CO₂ capture also requires efficient ion and CO₂ transport. TAP-1000, for example, shows a much higher capture rate than YP-80F despite their similarly high surface areas¹⁸, highlighting the importance of pore architecture and transport pathways.

Energy consumption shows a weaker correlation with S_{BET} as it reflects both material properties and device operation (Fig. 4c). A high-surface-area carbon may lower the energy consumed per mole of captured CO₂ by increasing uptake, but the overall energy consumption also depends on the device architecture (e.g., electrode configuration and loading) and charging protocols (e.g., voltage window, current density, and potentiostatic hold time). Consequently, energy values reported for different cell configurations and operating protocols should not be compared without accounting for these conditions.

Thus, S_{BET} is most useful as a descriptor of potential interfacial area, whereas capture rate and energy consumption depend increasingly on pore accessibility and device operating conditions.

4.2 Pore structure

Pore structure determines both the electrochemically accessible interfacial area and the transport of ions and CO₂-derived species within electrolyte-filled carbon pores. Insights from supercapacitor studies provide a useful starting point: micropores provide large interfacial area for electric-double-layer formation and, in sufficiently narrow pores, can alter ion solvation and packing, whereas mesopores provide less restricted pathways for ion transport^{38,39}. In SSA, pore structure must additionally accommodate dissolved CO₂ and carbonate species, making the balance between interfacial area and mass transport particularly important.

Within comparable material series, total pore volume can correlate positively with both CO₂ capture capacity and rate (Fig. 4d), but pore volume alone is not predictive. Larger pore volume can improve electrolyte infiltration and provide space for dissolved CO₂-derived species^{18,29}, while its effective utilization also depends on pore-size distribution and pore connectivity. **Micropores** provide substantial interfacial area for charge storage and can promote CO₂ enrichment through nanoconfinement²⁵, but excessive microporosity may restrict ion and CO₂ transport and reduce surface utilization. In contrast, **mesopores** can reduce transport limitations and improve access to microporous interfacial regions. Consistent with this picture, mesopore-rich TAP-1000 exhibits a much higher capture rate than YP-80F under high-current operation (Fig. 4e)¹⁸. However, excessive mesoporosity may reduce volumetric surface area and charge-storage capacity, highlighting the need for a hierarchical pore structure rather than maximization of a single pore regime.

At larger length scales, **macropores** may become increasingly important in thick electrodes and flow systems by facilitating electrolyte penetration and gas delivery. Beyond pore size, pore-network connectivity and tortuosity may further govern rate performance. Highly tortuous pathways increase effective diffusion distances and transport resistance, whereas more direct and interconnected pathways favor ion and CO₂ transport. Although rarely quantified in SSA studies, these descriptors may become particularly important for high-loading and high-rate electrodes.

4.3 Surface chemistry and functionalization

Surface chemistry is a critical but still underexplored parameter for carbon electrodes in SSA. In supercapacitors, heteroatoms such as O, N, B, S, and P may improve wettability, modify electronic structure, increase pseudocapacitance, and alter ion adsorption at the carbon/electrolyte interface⁴⁰⁻⁴². In SSA, surface functionalities may additionally influence the local ionic environment, pH changes, carbonate/bicarbonate equilibria, and interactions with dissolved CO₂ and CO₂-derived species.

Oxygen-containing groups can influence SSA by changing wettability, pore accessibility, charge storage, and interfacial ion distributions. Fig. 4f shows that the relationship between oxygen content and CO₂ capacity is non-monotonic, partly because oxygen content often varies together with surface area, pore structure, and conductivity, making it difficult to isolate the effect of oxygen alone. Xu *et al.* compared pristine and oxidized YP-80F with similar pore structures²⁷. Although oxidation increased capacitance, CO₂ adsorption capacities decreased, showing that higher oxygen content or capacitance does not necessarily translate into improved SSA performance.

The effect of oxygen also depends on functional-group identity. Carboxyl, lactone, phenolic, carbonyl, chromene, and pyrone groups⁴³ differ in acidity/basicity, wettability, ion affinity, and interfacial reactivity. Their impact therefore cannot be described solely by total oxygen content, but the chemical identity and local environment of these groups (e.g., interactions with electrolyte ions and CO₂-derived species) are also important. Oxygen functionalities should therefore be optimized rather than maximized. Suitable oxygen groups may improve electrolyte wetting and pore accessibility, whereas excessive oxidation can adversely impact CO₂ capture performance by blocking accessible pores, increasing resistance, or introducing unwanted Faradaic reactions. The key design target is therefore to balance wettability, conductivity, and pore accessibility so that stored charge can be efficiently coupled to CO₂ uptake.

The role of nitrogen and other heteroatoms remains less established. Nitrogen species such as pyridinic, pyrrolic, graphitic, and amine-like groups may modify electronic conductivity, wettability, surface basicity, and the local ionic environment⁴⁴. Basic nitrogen groups may also influence interactions with dissolved CO₂ species and local acid-base chemistry, although their specific role in SSA remains unclear. Direct experimental evidence linking individual nitrogen configurations to SSA capacity, rate, or energy consumption is still limited. The effects of B, P, and S doping are even less explored.

Future studies should therefore move beyond total heteroatom content toward well-defined functionalities and compositions. Model carbons with controlled oxygen or nitrogen configurations but similar pore-size distributions and surface areas are needed to separate chemical effects from textural effects. More specific molecular functionalization strategies, including quinone-modified carbons and COF-based composite electrodes, have been discussed in previous sections and are not considered in detail here.

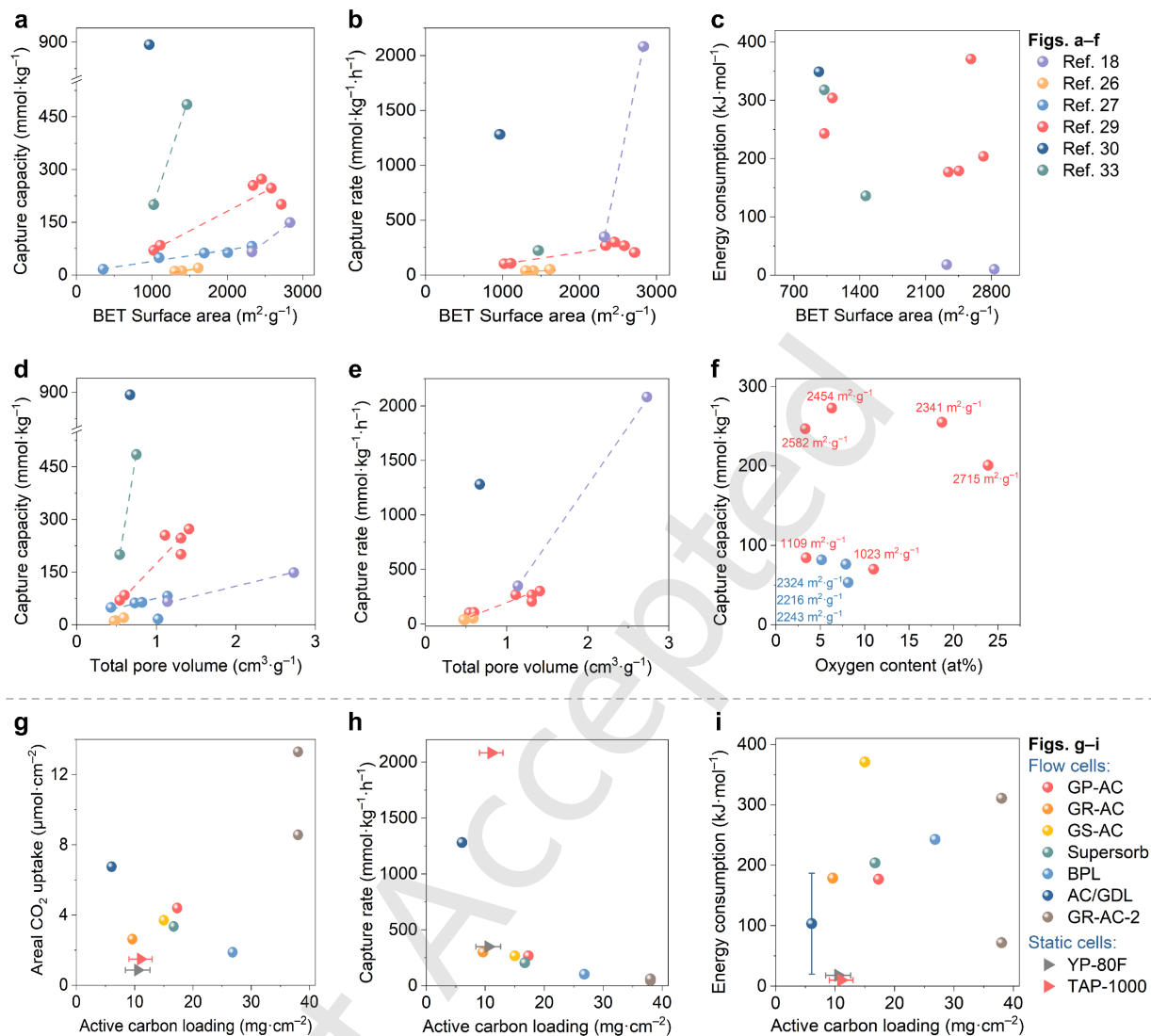


Fig. 4 Correlating carbon electrode properties with CO₂ capture performance in supercapacitive swing adsorption. a–c, Relationship between S_{BET} and CO₂ capture capacity, rate, and energy consumption. d, e, Relationship between total pore volume and CO₂ capture capacity and rate. f, Relationship between surface oxygen content and CO₂ capture capacity. g–i, Relationship between active-material loading and areal CO₂ capture capacity, rate, and energy consumption. Data extracted from Refs. 18,26,27,29,30,33,35 and replotted by the authors. The dashed lines in Figs. 4a–e are intended as guides within comparable material series rather than universal correlations, as these studies may use different electrode materials, cell configurations, gas compositions, and charging protocols.

4.4 Mass loading and electrode utilization

Active carbon loading is a key practical parameter in SSA because it determines how much CO₂ can be captured per unit electrode area. Low-loading, thin electrodes minimize ion- and CO₂-transport limitations and are therefore useful for mechanistic and material-comparison studies¹⁸. Practical devices, however, require higher loadings to achieve sufficient areal capture capacity.

Fig. 4g shows that areal CO₂ uptake generally increases with loading, provided that the added active material remains effectively utilized. For example, high-loading BPL electrodes exhibit relatively low areal uptake, whereas GR-AC electrodes with loadings approaching 40 mg·cm⁻² achieve higher areal

uptake of 12.6 μmol·cm⁻²²⁹. This comparison shows the importance of sufficient electrolyte penetration, gas transport, and electronic conduction throughout the electrode.

The effects of loading on capture rate and energy consumption are less direct (Figs. 4h, i). Increasing electrode thickness can lengthen ion- and gas-transport pathways and increase resistance, potentially reducing rate performance. Some comparatively low-loading electrodes such as TAP-1000 and activated-carbon/gas-diffusion-layer (AC/GDL) exhibit high capture rates. However, because these datasets span different carbon materials and cell architectures, they do not establish a universal inverse relationship between loading and capture rate.

Energy consumption likewise shows a non-monotonic relationship with loading, as it is influenced by both electrode properties and operating conditions. In addition to electrode resistance, electrolyte composition, cell architecture, and charging protocol can strongly affect the energy required per mole of captured CO₂. For example, TAP-1000 achieves high capture rates and low energy consumption at modest loading, whereas some higher-loading electrodes exhibit substantially larger energy penalties. Thus, the energetic effect of increasing loading depends on how effectively the added material can be utilized without introducing excessive transport or resistance losses.

Overall, increasing loading can increase areal CO₂ uptake only when the added material remains effectively utilized. However, thicker electrodes may introduce longer ion/CO₂ transport pathways, incomplete wetting, higher resistance, and binder-induced pore blockage, thereby reducing active-material utilization. Practical SSA electrodes must therefore maintain efficient ion/CO₂ transport and electronic conduction at high loading. As Figs. 4g–i compile data obtained using different materials, cell architectures, and operating conditions, they should be interpreted as maps of reported performance rather than universal loading–performance relationships.

4.5 Empirical electrode design principles

The SPRs discussed above suggest three key design principles for SSA carbon electrodes. First, high S_{BET} is beneficial only when the surface is electrochemically accessible, making accessible surface area and pore connectivity more meaningful than S_{BET} alone. Second, an optimized pore hierarchy is desirable. Micropores provide interfacial area for charge storage and CO₂ enrichment, whereas larger pores facilitate ion and CO₂ transport. Third, surface chemistry should be tuned to improve wettability, interfacial charge storage, and CO₂ uptake without compromising conductivity or stability.

These material-level advantages must be retained at practical electrode loadings. Electrode architecture should therefore maintain pore accessibility, ion/CO₂ transport, and electronic conduction throughout the electrode thickness through appropriate pore connectivity, binder distribution, and current collection.

Carbon structure, however, should not be optimized in isolation. Electrolyte composition, gas feed, flow conditions, and charging protocol can strongly influence how effectively a given electrode performs. Future SSA electrodes should therefore be evaluated under realistic conditions using both material- and device-level metrics, including gravimetric and areal CO₂ capacity, capture rate, energy consumption, and cycling stability. Together, these principles provide a basis for moving beyond empirical screening of available carbons toward electrodes deliberately tailored to the electrochemical and transport requirements of SSA.

5 Key challenges and future opportunities

5.1 Understanding CO₂ capture mechanisms

Despite recent progress in SSA performance, the molecular mechanisms governing electrochemical CO₂ capture remain incompletely understood¹⁵. This knowledge gap limits mechanism-guided materials design and the interpretation of performance differences across SSA systems. Key unresolved questions include how CO₂ and CO₂-derived species enter,

move through, and redistribute within electrolyte-filled porous electrodes during polarization; how local acid-base and carbonate equilibria evolve during capture and regeneration; and how these processes depend on carbon structure, electrolyte composition, cell configuration, and operating conditions.

One major obstacle is the lack of well-defined model materials. Commercial porous carbons have been essential for establishing SSA principles. Still, their heterogeneous pore networks, surface chemistry, and particle morphologies make it difficult to attribute the contribution of individual structural or chemical parameters. Consequently, robust SPRs remain difficult to establish. Future studies should develop model carbons with independently tunable pore structure and surface chemistry. Such material libraries could help identify which structural descriptors control CO₂ capture capacity, kinetics, charge efficiency, and cycling stability.

Another key limitation is the limited direct experimental evidence for CO₂ speciation and transport within electrified carbon pores. The spatial and temporal evolution of dissolved CO₂, HCO₃[−], CO₃^{2−}, protons, and supporting electrolyte ions remains largely unresolved. Resolving these processes will require complementary *ex situ*, *in situ*, and *operando* methods. *Ex situ* measurements can identify stable intermediates, products, and composition changes in the electrode/electrolyte after capture or regeneration, whereas *in situ* and *operando* methods are needed to track dynamic changes in CO₂ speciation, ion redistribution, local pH, and electrode charging in real time under applied potentials. Techniques including NMR/infrared/Raman spectroscopy, electrochemical quartz crystal microbalance (EQCM), X-ray techniques, and electrochemical impedance spectroscopy (EIS) can provide complementary insights into molecular speciation, mass changes and charge/ionic transport processes (Fig. 5a)⁴⁵.

Combining model electrodes with advanced characterization and multiscale simulations should clarify how carbon structure governs interfacial processes and macroscopic CO₂ capture performance. Such understanding is essential for moving SSA from empirical optimization toward predictive, mechanism-guided material and device design.

5.2 Advancing material and device design

Building on improved mechanistic understanding, future SSA development will require materials and devices designed specifically for electrochemical CO₂ capture rather than adapted from conventional supercapacitors or CO₂ physisorbents. Many conventional carbon-based SSA systems still exhibit lower capture capacities of 40–200 mmol·kg^{−1}^{17,27} than those of porous adsorbents (>400 mmol·kg^{−1}⁴⁶), amine-functionalized sorbents (2,000–5,000 mmol·kg^{−1}^{47,48}), and aqueous amine solutions used in amine scrubbing processes (1,500–3,000 mmol·kg^{−1}⁴⁹), although recent tailored porous carbons and redox-active electrodes have narrowed this gap. A similar challenge remains for capture rate, with most SSA systems operating at 100–500 mmol·kg^{−1}·h^{−1}, lower than those of solid amine sorbents (~1,000 mmol·kg^{−1}·h^{−1}^{47,48}) and industrial amine scrubbing (>5,000 mmol·kg^{−1}·h^{−1}⁴⁹). Direct quantitative comparisons across capture technologies should be made cautiously because gas compositions, sorbent/electrode mass normalization, operating conditions, and kinetic definitions differ substantially. Despite these limitations, SSA offers distinctive advantages including electrically controlled

capture and regeneration, potentially low energy consumption, and durable cycling.

Closing this performance gap will require co-optimization of carbon structure, electrode architecture, electrolyte composition, and operating conditions rather than improvement of individual parameters in isolation (Fig. 5b). At the material level, porous carbons with tailored pore architectures, connected transport pathways, and controlled surface chemistry are needed to improve both CO₂ uptake and charge utilization. Functionalized carbons, COFs, and hybrid electrodes may provide additional routes to increase capture capacity, rate, selectivity, and durability, but their advantages should be evaluated using consistent SSA protocols and well-defined structural descriptors.

Beyond conventional particulate carbons, low-dimensional carbon materials may offer new opportunities for controlling ion transport and interfacial chemistry in SSA. Graphene and related layered materials are of particular interest for membrane-integrated systems because their interlayer spacing and surface chemistry can be tuned to regulate ionic transport and selectivity. Such materials could function as ion-selective separators or interfacial layers, particularly in complex aqueous feeds containing competing ions and foulants. Their established use in membrane separation and capacitive deionization provides useful design concepts that may be transferable to SSA, although their applicability to SSA remains largely unexplored. Future studies should therefore determine whether these materials can provide selective ion transport and electrochemical stability without introducing excessive resistance or fabrication complexity. Other emerging materials, including conductive metal-organic frameworks and MXenes, may also offer new ways to control charge storage, ion transport, and interfacial CO₂ chemistry, but their relevance to SSA will depend on conductivity, chemical stability, processability, and compatibility with the electrolyte environment.

At the electrode level, greater attention should be given to active-material loading, thickness, binder distribution, and current collectors. Cell design should likewise address electrolyte management, separator/membrane selection, and gas-liquid flow and contact patterns. In particular, flow-cell engineering strategies developed for electrochemical conversion systems may provide useful guidance for controlling gas and electrolyte delivery, minimizing transport resistance, and improving active-material utilization in SSA. Together, these electrode- and cell-level factors directly influence CO₂ capture performance and energy consumption yet remain insufficiently studied in current SSA research. Equally important is the development of standardized testing protocols that clearly define electrochemical cycling conditions, gas compositions and flow conditions, and methods for quantifying CO₂ uptake and release. Without consistent testing and reporting, meaningful comparison across materials and devices remains difficult.

Overall, the next stage of SSA research should shift from adapting existing carbon materials toward mechanism-guided co-design of materials, electrodes, devices, and operating protocols. Linking molecular-level understanding with electrode and process engineering will be essential for improving CO₂ capture capacity, rate, energy efficiency, selectivity, and long-term stability.

5.3 Evaluation under realistic operating conditions and scale-up

To date, most SSA studies have been conducted in lab-scale cells under simplified conditions, typically using small electrode areas, pure or concentrated CO₂ streams, and static or low-speed flow operation. While these studies have provided valuable mechanistic insights, their performance may not directly translate to practical carbon-capture applications.

In realistic scenarios, including post-combustion flue-gas treatment, direct air capture, and seawater-based carbon removal, SSA systems must operate with dilute and/or chemically complex feeds, continuous processing, larger electrode areas, and higher active-material loadings (Fig. 5c). These conditions introduce application-specific challenges. Gas-phase capture must tolerate low CO₂ concentrations, humidity, and competing gas components, whereas seawater-based systems must operate in the presence of high ionic strength, competing ions, and potential fouling or scaling. As devices are scaled up, process-level factors such as gas/liquid mass transfer, electrolyte management, and impurity tolerance may become as important as the intrinsic properties of the carbon electrode itself.

Future studies should therefore emphasize scalable flow-through and membrane-integrated SSA architectures tested under application-relevant conditions. Performance evaluation should report CO₂ capacity on gravimetric, areal, and volumetric bases, together with capture kinetics, energy and charge efficiency, cycling stability, and tolerance to realistic feeds. Ultimately, scalable deployment of SSA will require co-design of carbon materials, electrode architecture, cell configurations, and operating conditions, along with long-term demonstrations of stable and energy-efficient CO₂ capture.

5.4 Integration of CO₂ capture and utilization

The integration of CO₂ capture with downstream utilization remains an important but underdeveloped direction for electrochemical carbon management. Over the past decades, significant advances have been made in electrochemical CO₂ capture⁵⁰, electrocatalytic and photo-electrocatalytic CO₂ conversion, and metal-CO₂ batteries⁵¹. Despite their shared objective of closing the carbon cycle, these technologies have largely developed independently, with limited integration of CO₂ capture, enrichment, transport, and conversion^{52,53}.

A central challenge is the mismatch between the operating requirements of CO₂ capture and conversion. These processes often require different electrolyte chemistries and pH ranges, and may require different electrode and reactor configurations for managing gas-liquid contact. Moreover, captured carbon may exist as dissolved CO₂, HCO₃⁻, CO₃²⁻, or other bound species, creating additional challenges for direct transport and conversion within an integrated system. SSA could provide a useful electrochemical front end to bridge CO₂ capture and utilization, because polarization can regulate capture, enrichment, and release of CO₂-derived species. Future systems may combine SSA with electrocatalytic CO₂ reduction, bicarbonate electrolysis, or metal-CO₂ batteries, with the aim of transferring captured carbon directly into a compatible conversion environment and reducing intermediate desorption, purification, compression, or transport steps (Fig. 5d). Beyond point-source capture, SSA may also serve as an enrichment step for dilute CO₂ sources from air and seawater.

Integration with other electrochemical separation processes may provide additional opportunities for SSA. For example, combining SSA with capacitive deionization or related ion-separation technologies could help regulate ionic composition and carbonate equilibria in seawater-based carbon removal. Such concepts remain largely unexplored, and future implementations should minimize added resistance, energy demand, and process complexity. Successful integration will ultimately require chemical and operational compatibility between the capture and conversion steps. Advances in carbon materials, electrolyte and reactor design may allow SSA to evolve from a stand-alone capture process toward a component of broad electrochemical carbon-management systems.

5.5 Techno-economic analysis and life-cycle assessments

High SSA performance at the lab scale does not necessarily translate to practical deployment. A major gap in current research is the limited use of techno-economic analysis (TEA) and life-cycle assessment (LCA), as most studies focus on capture performance. Consequently, the economic and environmental viability of SSA at scale remains poorly constrained.

TEA is essential for assessing whether SSA can compete with established carbon-capture technologies. Beyond material costs, TEA should account for capital expenditures associated with electrodes, reactors, and balance-of-plant, as well as operating costs such as electricity, electrolyte management, maintenance, and component replacement (Fig. 5e). These factors determine the overall cost of CO₂ capture and enable comparison with mature technologies such as amine scrubbing. Such comparisons should use consistent system boundaries and

operating assumptions, particularly for CO₂ concentration, capture fraction, regeneration conditions, and electricity price.

LCA is equally important for determining whether SSA provides a genuine climate benefit. Many advanced carbon electrodes require energy-intensive synthesis, including high-temperature carbonization and activation, which can contribute substantially to their embodied energy use and greenhouse-gas emissions. Nevertheless, these impacts may be mitigated through the use of sustainably sourced biomass-derived precursors, whose carbon originates from atmospheric CO₂ fixation, as well as through optimized synthesis pathways that lower carbonization temperatures and improve carbon yields, thereby reducing the external energy demand of carbon production. In addition, heat released during exothermic stages of carbonization and the recovery and combustion of energy-rich gaseous by-products, such as CO, could partially offset the external heat demand. Such strategies may therefore help reduce the energy and carbon footprint of porous-carbon production. LCA should therefore account for impacts associated with material production, device fabrication, electrolyte use and replacement, electricity consumption, and end-of-life treatment. These impacts should then be compared with CO₂ emissions avoided/removed by the process.

Future SSA research should incorporate TEA and LCA alongside electrochemical and capture-performance metrics. This will allow more meaningful comparison between materials, device configurations, and operating conditions. Ultimately, the practical viability of SSA will depend not only on high capture capacity and low energy consumption, but also on competitive capture costs, low life-cycle emissions, scalable manufacturing, and sufficiently long material and device lifetimes.

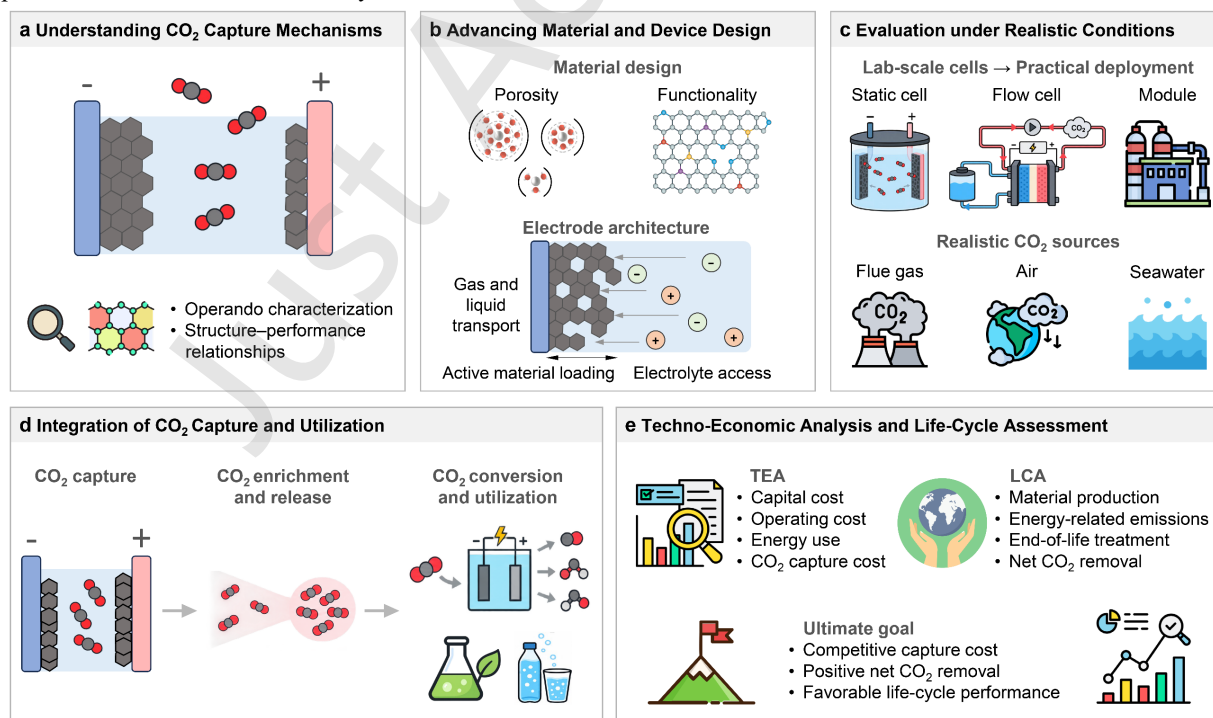


Fig. 5 Future research directions for supercapacitive swing adsorption toward practical electrochemical CO₂ capture. **a**, Mechanistic understanding. **b**, Advancing material and device design. **c**, Evaluation under realistic operating conditions. **d**, Integration of CO₂ capture and utilization. **e**, Techno-economic analysis and life-cycle assessment for practical SSA deployment.

6 Conclusion

SSA has evolved from an early proof-of-concept based on commercial porous carbons into a broader family of electrochemical CO₂-capture systems incorporating tailored porous carbons, redox-functionalized electrodes, optimized electrolytes, and increasingly diverse device architectures. Across these developments, the carbon electrode emerges not simply as a conductive scaffold but as an active electrochemical interface that regulates charge storage, ion distribution, local CO₂ enrichment, and interfacial acid–base chemistry.

Several SPRs can now be identified, although none acts as a universal descriptor on its own. High S_{BET} is beneficial only when the corresponding surface is electrochemically accessible, while multiscale pore structures that combine microporous interfacial area with larger transport pathways can improve the balance between CO₂ uptake and capture rate. Quinone functionalization has demonstrated the potential of introducing specific redox-active sites to enhance electrochemical CO₂ capture, while the influence of intrinsic surface functionalities of porous carbons on SSA remains poorly understood and requires further systematic investigation. Beyond intrinsic material properties, electrode thickness and active-material loading, together with electrolyte composition, cell configuration, and operating protocols, further determine how effectively these material properties translate into practical performance.

Future progress therefore requires moving from empirical optimization toward mechanism-guided design. Model carbons with independently controlled pore structure and surface chemistry, combined with *ex situ*, *in situ*, and *operando* measurements of interfacial pH, ion distributions, and CO₂ speciation, will be important for establishing more transferable SPRs. At the same time, high-loading flow electrodes should be evaluated under realistic operating conditions to determine whether gains observed in model systems persist at practical scales. Integration with CO₂ utilization or other electrochemical separation processes may further broaden the role of SSA, but its practical viability will ultimately depend on achieving improved capture capacity and rate without sacrificing energy efficiency, long-term stability, manufacturability, and favorable techno-economic and life-cycle performance.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper are available from the corresponding author upon request.

Acknowledgements

J. Li and F. Li acknowledge the support from the UNSW 2026 Horizon Europe GRIP Initiator Grant and the Australian Research Council (ARC, FL190100126; CE230100032). J. Li acknowledges the Marie Skłodowska-Curie Actions under the European Union's Horizon Europe research and innovation programme (Grant Agreement No. 101268911).

Author contributions

J. Li conducted the literature review, prepared the original draft and figures, and revised the manuscript. F. Li provided input on the future perspectives of SSA, revised the manuscript, and verified the copyright information for reproduced or adapted figures. Both authors approved the final version of the manuscript.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Use of AI statement

During the preparation of this work, the authors used ChatGPT to polish the language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the original author(s) and the source, provide a link to the license, and indicate if changes were made. See <https://creativecommons.org/licenses/by/4.0/>

© The author(s) 2026. Published by Tsinghua University Press.

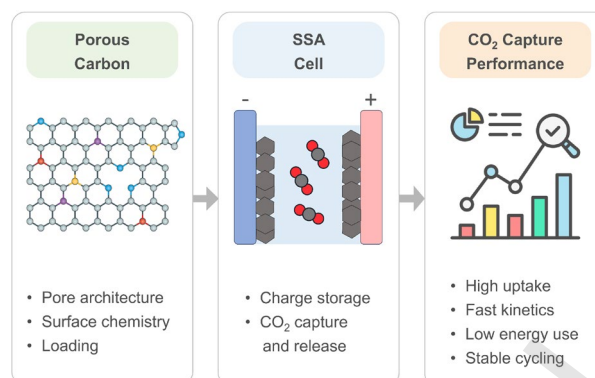
References

- [1] IPCC, *Climate Change 2023: Synthesis Report*, Geneva, **2023**.
- [2] Boot-Handford, M. E.; Abanades, J. C.; Anthony, E. J.; Blunt, M. J.; Brandani, S.; Mac Dowell, N.; Fernandez, J. R.; Ferrari, M.-C.; Gross, R.; Hallett, J. P.; Haszeldine, R. S.; Heptonstall, P.; Lyngfelt, A.; Makuch, Z.; Mangano, E.; Porter, R. T. J.; Pourkashanian, M.; Rochelle, G. T.; Shah, N.; Yao, J. G.; Fennell, P. S., Carbon capture and storage update. *Energy Environ. Sci.* **2014**, *7*, 130–189.
- [3] Rochelle, G. T., Amine scrubbing for CO₂ capture. *Science* **2009**, *325*, 1652–1654.
- [4] Salaudeen, S. A.; Acharya, B.; Dutta, A., CaO-based CO₂ sorbents: A review on screening, enhancement, cyclic stability, regeneration and kinetics modelling. *J. CO₂ Util.* **2018**, *23*, 179–199.
- [5] Wang, Y.; Zhang, K.; Feng, J.; Sun, X.; Li, C.; Wang, K.; Zhang, X.; Ma, Y., Supercapacitive swing adsorption of carbon dioxide: current status and perspectives. *Batter. Supercaps* **2023**, *6*, 202300283.
- [6] Sun, K.; Tebyetekerwa, M.; Zhang, H.; Zeng, X.; Wang, Z.; Xu, Z.; Rufford, T. E.; Zhang, X., Electrode, electrolyte, and membrane materials for electrochemical CO₂ capture. *Adv. Energy Mater.* **2024**, *14*, 2400625.
- [7] Sharifian, R.; Wagterveld, R. M.; Digdaya, I. A.; Xiang, C.; Vermaas, D. A., Electrochemical carbon dioxide capture to close the carbon cycle. *Energy Environ. Sci.* **2021**, *14*, 781–814.
- [8] Rahimi, M.; Khurram, A.; Hatton, T. A.; Gallant, B., Electrochemical carbon capture processes for mitigation of CO₂ emissions. *Chem. Soc. Rev.* **2022**, *51*, 8676–8695.
- [9] Pang, S.; Jin, S.; Yang, F.; Alberts, M.; Li, L.; Xi, D.; Gordon, R. G.; Wang, P.; Aziz, M. J.; Ji, Y., A phenazine-based high-capacity and high-stability electrochemical CO₂ capture cell with coupled electricity storage. *Nat. Energy* **2023**, *8*, 1126–1136.
- [10] Seo, H.; Hatton, T. A., Electrochemical direct air capture of CO₂ using neutral red as reversible redox-active material. *Nat. Commun.* **2023**, *14*, 313.

- [11] Li, X.; Zhao, X.; Liu, Y.; Hatton, T. A.; Liu, Y., Redox-tunable Lewis bases for electrochemical carbon dioxide capture. *Nat. Energy* **2022**, *7*, 1065.
- [12] Barlow, J. M.; Yang, J. Y., Oxygen-stable electrochemical CO₂ capture and concentration with quinones using alcohol additives. *J. Am. Chem. Soc.* **2022**, *144*, 14161–14169.
- [13] Khan, F. ul H.; Bilal, M.; Li, J.; Xu, X.; Landskron, K., Supercapacitive swing adsorption of CO₂: advances and future prospects. *Trends Chem.* **2025**, *7*, 43–55.
- [14] Yeo, E.; Shin, H.; Kim, T.; Kim, S.; Kang, J. S., Electrochemically driven capacitive CO₂ capture technologies. *J. Environ. Chem. Eng.* **2025**, *13*, 116092.
- [15] Seyffert, M.; Coady, Z.; Walsh, C.; Wiesner, S. E.; Taylor, J. S.; Mapstone, G. E.; Forse, A. C., Why CO₂ capture via supercapacitive swing adsorption needs a theory, not just tweaks. *Chem. Sci.* **2026**, *17*, 16036–16049.
- [16] Kokoszka, B.; Jarrah, N. K.; Liu, C.; Moore, D. T.; Landskron, K., Supercapacitive swing adsorption of carbon dioxide. *Angew. Chem. Int. Ed.* **2014**, *53*, 3698–3701.
- [17] Xu, Z.; Liu, X.; Mapstone, G.; Coady, Z.; Seymour, C.; Wiesner, S. E.; Menkin, S.; Forse, A. C., Breaking supercapacitor symmetry enhances electrochemical carbon dioxide capture. *J. Am. Chem. Soc.* **2025**, *147*, 16189–16197.
- [18] Xu, Z.; Pedersen, A.; Shimizu, S.; Yoshii, T.; Nishihara, H.; Titirici, M.; Barrio, J.; Forse, A. C., Exploring improved supercapacitor electrodes for electrochemical carbon dioxide capture. *ACS Electrochem.* **2026**, *2*, 1115–1120.
- [19] Wiesner, S. E.; Coady, Z.; Xu, Z.; Seyffert, M.; Forse, A. C., Supercapacitor-based CO₂ capture enhanced by electrolyte pH control. *J. Mater. Chem. A* **2026**, *14*, 20804–20814.
- [20] Liu, C.; Landskron, K., Design, construction, and testing of a supercapacitive swing adsorption module for CO₂ separation. *Chem. Commun.* **2017**, *53*, 3661–3664.
- [21] Zhu, S.; Ma, K.; Landskron, K., Relationships between the charge-discharge methods and the performance of a supercapacitive swing adsorption module for CO₂ separation. *J. Phys. Chem. C* **2018**, *122*, 18476–18483.
- [22] Zhu, S.; Li, J.; Toth, A.; Landskron, K., Relationships between electrolyte concentration and the supercapacitive swing adsorption of CO₂. *ACS Appl. Mater. Interfaces* **2019**, *11*, 21489–21495.
- [23] Zhu, S.; Li, J.; Toth, A.; Landskron, K., Relationships between the elemental composition of electrolytes and the supercapacitive swing adsorption of CO₂. *ACS Appl. Energy Mater.* **2019**, *2*, 7449–7456.
- [24] Binford, T. B.; Mapstone, G.; Temprano, I.; Forse, A. C., Enhancing the capacity of supercapacitive swing adsorption CO₂ capture by tuning charging protocols. *Nanoscale* **2022**, *14*, 7980–7984.
- [25] Coady, Z.; Brookes, S. G. H.; Shen, Z.; Rhodes, B. J.; Mapstone, G.; Xu, Z.; Yu, W.; Nishihara, H.; Schran, C.; Michaelides, A.; Forse, A. C., Unexpected oversolubility of CO₂ measured at electrode-electrolyte interfaces. *J. Am. Chem. Soc.* **2025**, *147*, 36310–36319.
- [26] Wang, Y.; Sun, X.; Zhang, K.; Feng, J.; Sun, X.; Li, C.; Wang, K.; Zhang, X.; Ma, Y., Effects of activated carbon types on the CO₂ supercapacitive swing adsorption performances. *J. Solid State Electrochem.* **2026**, *30*, 17–30.
- [27] Xu, Z.; Mapstone, G.; Coady, Z.; Wang, M.; Spreng, T. L.; Liu, X.; Molino, D.; Forse, A. C., Enhancing electrochemical carbon dioxide capture with supercapacitors. *Nat. Commun.* **2024**, *15*, 7851.
- [28] Liu, X.; Lyu, D.; Merlet, C.; Leesmith, M. J. A.; Hua, X.; Xu, Z.; Grey, C. P.; Forse, A. C., Structural disorder determines capacitance in nanoporous carbons. *Science* **2024**, *384*, 321.
- [29] Bilal, M.; Li, J.; Landskron, K., Enhancing supercapacitive swing adsorption of CO₂ with advanced activated carbon electrodes. *Adv. Sustain. Syst.* **2023**, *7*, 2300250.
- [30] Sun, K.; Tebyetekerwa, M.; Zhang, H.; Duignan, T. T.; Evans, R.; Ge, L.; Sun, Y.; Ge, Y.; Wang, Z.; Xing, C.; Yang, J.; Zeng, X., Membrane-separated electrodes enable high-rate low-energy electrochemical carbon capture. *Sci. Adv.* **2026**, *12*, eac3918.
- [31] Hartley, N. A.; Xu, Z.; Kress, T.; Forse, A. C., Correlating the structure of quinone-functionalized carbons with electrochemical CO₂ capture performance. *Mater. Today Energy* **2024**, *45*, 101689.
- [32] Khan, M. A.; Xu, Z.; Muzammil, M.; Bird, S.; Munawar, M.; Salam, F.; Hartley, N. A.; Taylor, J.; Amin, K.; Ling, J.; Enniful, H. R. N. B.; Ali, N. Z.; Hetze, K.; Cao, S.; Lu, Y.; Wei, Z.; Oschatz, M.; Milner, P. J.; Forse, A. C., Electrochemical CO₂ capture by a quinone-based covalent organic framework. *J. Am. Chem. Soc.* **2025**, *147*, 47036–47043.
- [33] Bilal, M.; Li, J.; Guo, H.; Landskron, K., High-voltage supercapacitive swing adsorption of carbon dioxide. *Small* **2023**, *19*, 2207834.
- [34] Bilal, M.; Li, J.; Kumar, N.; Mosevitzky, B.; Wachs, I. E.; Landskron, K., Oxygen-assisted supercapacitive swing adsorption of carbon dioxide. *Angew. Chem. Int. Ed.* **2024**, *63*, e202404881.
- [35] Li, J.; Bilal, M.; Landskron, K., Scaling supercapacitive swing adsorption of CO₂ using bipolar electrode stacks. *Small* **2024**, *20*, 2303243.
- [36] Mapstone, G.; Kamsma, T. M.; Xu, Z.; Jones, P. K.; Lee, A. A.; Temprano, I.; Lee, J.; De Volder, M. F. L.; Forse, A. C., Understanding the mechanism of electrochemical CO₂ capture by supercapacitive swing adsorption. *ACS Nano* **2025**, *19*, 4242–4250.
- [37] Hartley, N. A.; Pugh, S. M.; Xu, Z.; Leong, D. C. Y.; Jaffe, A.; Forse, A. C., Quinone-functionalised carbons as new materials for electrochemical carbon dioxide capture. *J. Mater. Chem. A* **2023**, *11*, 16221–16232.
- [38] Chmiola, J.; Yushin, G.; Gogotsi, Y.; Portet, C.; Simon, P.; Taberna, P. L., Anomalous increase in carbon capacitance at pore size less than 1 nanometer. *Science* **2006**, *313*, 1760–1763.
- [39] Li, J.; Ge, K.; Grammenos, A. O.; Taberna, P.; Simon, P.; Antonietti, M.; Odziemek, M., Understanding multi-stage charge storage on nanoporous carbons in Zn-ion hybrid capacitors. *Adv. Mater.* **2025**, *37*, 2502422.
- [40] Wei, F.; Zeng, Y.; Guo, Y.; Li, J.; Zhu, S.; Gao, S.; Zhang, H.; He, X., Recent progress on the heteroatom-doped carbon cathode for zinc ion hybrid capacitors. *Chem. Eng. J.* **2023**, *468*, 143576.
- [41] Yang, M.; Zhou, Z., Recent breakthroughs in supercapacitors boosted by nitrogen-rich porous carbon materials. *Adv. Sci.* **2017**, *4*, 1600408.
- [42] Eren, E. O.; Esen, C.; Scoppola, E.; Song, Z.; Senokos, E.; Zschiesche, H.; Cruz, D.; Lauermann, I.; Tarakina, N. V.; Kumru, B.; Antonietti, M.; Giusto, P., Microporous sulfur-carbon materials with extended sodium storage window. *Adv. Sci.* **2024**, *11*, 2310196.
- [43] Lyu, D.; Märker, K.; Zhou, Y.; Zhao, E. W.; Gunnarsdóttir, A. B.; Niblett, S. P.; Forse, A. C.; Grey, C. P., Understanding sorption of aqueous electrolytes in porous carbon by NMR spectroscopy. *J. Am. Chem. Soc.* **2024**, *146*, 9897.
- [44] Zhang, E.; Wu, Y. C.; Shao, H.; Klimavicius, V.; Zhang, H.; Taberna, P. L.; Grothe, J.; Buntkowsky, G.; Xu, F.; Simon, P.; Kaskel, S., Unraveling the capacitive charge storage mechanism of nitrogen-doped porous carbons by EQCM and ssNMR. *J. Am. Chem. Soc.* **2022**, *144*, 14217.
- [45] Ge, K.; Shao, H.; Lin, Z.; Taberna, P. L.; Simon, P., Advanced characterization of confined electrochemical interfaces in electrochemical capacitors. *Nat. Nanotechnol.* **2025**, *20*, 196.
- [46] Li, J.; Kossmann, J.; Zeng, K.; Zhang, K.; Wang, B.; Weinberger, C.; Antonietti, M.; Odziemek, M.; López-Salas, N., When high-temperature cesium chemistry meets self-templating: metal acetates as building blocks of unusual highly porous carbons. *Angew. Chem. Int. Ed.* **2023**, *62*, e202217808.
- [47] Zhu, X.; Ge, T.; Yang, F.; Lyu, M.; Chen, C.; O'Hare, D.; Wang, R., Efficient CO₂ capture from ambient air with amine-functionalized Mg–Al mixed metal oxides. *J. Mater. Chem. A* **2020**, *8*, 16421.
- [48] Lin, Y.; Yan, Q.; Kong, C.; Chen, L., Polyethyleneimine incorporated metal-organic frameworks adsorbent for highly selective CO₂ capture. *Sci. Rep.* **2013**, *3*, 1859.
- [49] Zhu, X.; Lu, H.; Wu, K.; Zhu, Y.; Liu, Y.; Liu, C.; Liang, B.,

- DBU-glycerol solution: a CO₂ absorbent with high desorption ratio and low regeneration energy. *Environ. Sci. Technol.* **2020**, *54*, 7570.
- [50] Zhu, P.; Wu, Z. Y.; Elgazzar, A.; Dong, C.; Wi, T. U.; Chen, F. Y.; Xia, Y.; Feng, Y.; Shakouri, M.; Kim, J. Y. (Timothy); Fang, Z.; Hatton, T. A.; Wang, H., Continuous carbon capture in an electrochemical solid-electrolyte reactor. *Nature* **2023**, *618*, 959.
- [51] Li, J.; Zhang, K.; Zhao, Y.; Wang, C.; Wang, L.; Wang, L.; Liao, M.; Ye, L.; Zhang, Y.; Gao, Y.; Wang, B.; Peng, H., High-efficiency and stable Li-CO₂ battery enabled by carbon nanotube/carbon nitride heterostructured photocathode. *Angew. Chem. Int. Ed.* **2022**, *61*, e202114612.
- [52] Liu, H.; An, L.; Wang, P.; Yu, C.; Zhang, J.; Shin, H.; Peng, B.; Li, J.; Li, M.; An, H.; Yu, J.; Chen, Y.; Wang, P.; Lee, K. S.; Lalit, K.; Liu, Z.; Farha, O. K.; Huang, W.; Liu, J. Z.; Qi, L.; Xie, K.; Sargent, E. H., Interconnected nanoconfining pore networks enhance catalyst CO₂ interaction in electrified reactive capture. *Nat. Commun.* **2025**, *16*, 6185.
- [53] Kim, Y.; Lees, E. W.; Donde, C.; Jewlal, A. M. L.; Waizenegger, C. E. B.; de Hepcée, B. M. W.; Simpson, G. L.; Valji, A.; Berlinguette, C. P., Integrated CO₂ capture and conversion to form syngas. *Joule* **2024**, *8*, 3106.

Table of Contents (TOC)



This Review provides a carbon-centered perspective on supercapacitive swing adsorption (SSA) for electrochemical CO₂ capture. It highlights the advances in porous carbon electrodes, discusses emerging structure–performance relationships and capture mechanisms, and outlines future directions toward scalable and energy-efficient SSA.