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Carbon Capture at Scale: Materials, Process Platforms, and Integration Strategies

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ABSTRACT

Carbon capture has become a central element of decarbonization strategies because it can reduce emissions from concentrated industrial sources while also enabling atmospheric CO_2 removal. This review re-examines the field through the combined lenses of process route, material performance, and system integration. Post-combustion, pre-combustion, oxy-fuel, and direct air capture pathways are compared alongside absorption, adsorption, membrane, and cryogenic separation technologies. The synthesis brings together bibliometric evidence, technology-readiness screening, and benchmarking of energy demand, cost, and environmental constraints reported in the literature. Particular attention is given to sorbent chemistry, structured contactors, humid operating conditions, and low-partial-pressure CO_2 capture. The results show that mature solvent systems remain dominant at industrial scale, whereas advanced solids, hybrid flowsheets, and intensified regeneration strategies are reshaping the performance frontier. The review also identifies integration with low-grade heat, renewable electricity, transport and storage networks, and carbon utilization pathways as decisive factors for scale-up. Overall, carbon capture is best viewed not as a single technology, but as an interconnected portfolio whose future depends on coordinated advances in materials, process engineering, infrastructure, and policy.

1. Introduction

Anthropogenic carbon dioxide emissions remain a defining driver of climate change, and limiting temperature rise to internationally discussed thresholds requires both deep emission reductions and additional carbon management capacity. [1], [2], [3], [4] Within that context, carbon capture has moved from being a niche process-engineering topic to a strategic component of net-zero planning, particularly for sectors in which direct electrification is difficult or insufficient. [5], [6], [7] Its relevance extends from conventional point-source capture in power and industrial systems to direct air capture (DAC), which targets the much more dilute CO_2 concentration of the atmosphere. [8], [9], [10]

At its core, carbon capture is a separation problem governed by thermodynamics, mass transfer, and reaction kinetics. [11], [12], [13] The main routes differ in feed composition, operating pressure, temperature window, and regeneration burden, which explains why no single technology is universally optimal. [14], [15], [16] Chemical absorption has long provided the industrial benchmark, but high regeneration duties, solvent degradation, corrosion, and process complexity continue to motivate alternatives. [17], [18], [19] In parallel, adsorption, membrane, and cryogenic systems have matured as credible pathways for selected duties, especially where energy integration, compactness, or high-purity CO_2 recovery is important. [20], [21]

Recent progress has been especially notable in advanced porous materials and structured contactors. [22], [23], [24] Zeolites, activated carbons, amine-functionalized silicas, MOFs, COFs, and polymer-derived sorbents have widened the design space for both flue-gas treatment and DAC, while monoliths, fibers, and lattice architectures have improved transport characteristics and reduced pressure drop. [25], [26], [27] Yet this rapid expansion has also made the field more fragmented. [28], [29] The purpose of the present review is therefore to reframe the literature in a comparative way, linking materials, capture routes, integration options, and scale-up constraints rather than discussing each area in isolation. [30], [31]

This need for comparative synthesis is increasingly important because the practical value of any capture technology is determined not only by its laboratory performance, but also by its compatibility with real operating environments. In point-source applications, flue-gas composition, contaminants, water vapor, temperature fluctuations, and pressure conditions can strongly influence selectivity, working capacity, sorbent stability, and regeneration energy. [14], [17], [20] For DAC, these challenges become even more pronounced because the very low atmospheric CO_2 concentration imposes stringent demands on contactor design, air handling, and process energetics. [8], [9], [25] As a result, materials that appear highly promising under controlled dry conditions may perform very differently once humidity, thermal cycling, and long-term degradation are taken into account. [22], [24], [26]

A further challenge is that the literature often advances in parallel streams with limited cross-comparison. Material-focused studies may emphasize equilibrium uptake, surface area, or selectivity, whereas process-oriented investigations prioritize pressure drop, heat integration, cycle time, and overall cost. [11], [15], [21] System-level studies, meanwhile, tend to evaluate capture technologies through techno-economic or policy lenses, sometimes without sufficient attention to the material-level constraints that ultimately govern deployability. [5], [6], [30]

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Nomenclature

Abbreviation
CCS – Carbon Capture and Storage
CCUS – Carbon Capture, Utilization, and Storage
DAC – Direct Air Capture
MEA – Monoethanolamine
MOF – Metal–Organic Framework
COF – Covalent Organic Framework
PSA – Pressure Swing Adsorption
OPEX – Operational Expenditure
TRL – Technology Readiness Level

Symbol
C_{CO2} – Concentration of carbon dioxide ($mol \cdot m^{-3}$)
q_t – Adsorbed amount at time t ($mmol \cdot g^{-1}$)
ΔH_{ads} – Heat of adsorption ($kJ \cdot mol^{-1}$)

This separation of scales can obscure the real trade-offs that define successful carbon capture systems, including the balance between high capacity and fast kinetics, between strong binding and low regeneration energy, and between compact process design and operational flexibility. [12], [13], [27]

The issue is not simply which technology captures the most CO_2, but which configuration can sustain reliable performance under realistic conditions while remaining economically and environmentally defensible. [16], [18], [31] Capture systems are now being evaluated not only on separation efficiency, but also on their integration with low-carbon heat and power, water demand, lifecycle emissions, and suitability for hard-to-abate sectors such as cement, steel, refining, aviation fuels, and negative-emission infrastructure. [4], [7], [10] These broader considerations have shifted the field away from narrow single-metric comparisons toward multi-criteria assessment frameworks that account for technical maturity, scalability, and regional deployment context. [6], [19], [29]

Accordingly, this review examines carbon capture through four interconnected dimensions. First, it compares the major capture routes and their governing process principles. [14], [15], [20] Second, it evaluates the evolving material landscape, with particular attention to how sorbent chemistry, pore architecture, and structural form influence separation performance under dry and humid conditions. [22], [23], [25] Third, it assesses process integration pathways, including hybrid capture configurations, waste-heat utilization, renewable coupling, and the role of structured contactors in improving transport and lowering parasitic penalties. [21], [24], [27] Finally, it discusses the scale-up challenges that continue to limit deployment, including stability, manufacturability, infrastructure dependence, and the gap between promising bench-scale results and commercially relevant operation. [28], [30], [31]

By organizing the field around these linked questions, the review aims to provide a clearer framework for understanding where the most meaningful advances are occurring and where unresolved bottlenecks remain. Rather than treating absorption, adsorption, membranes, cryogenic separation, and DAC as isolated topics, the discussion emphasizes their overlap, complementarities, and application-specific relevance. [17], [20], [30] In doing so, the review seeks to support a more integrated perspective on carbon capture, one that connects molecular-scale innovation to process design and system-level deployment in the broader pursuit of low-carbon and net-negative energy systems. [3], [5], [31]

2. Methodology

This review was structured to deliver a comparative and methodologically transparent synthesis of carbon capture technologies, materials, and deployment pathways. [32], [33], [34] The workflow combined systematic literature screening with bibliometric mapping and performance benchmarking so that the analysis could extend beyond narrative description and toward cross-study comparison. [35], [36] Sources were drawn from multidisciplinary databases and major international reports, including peer-reviewed journals, conference proceedings, technology roadmaps, and policy documents relevant to CCS, CCUS, and DAC. [37], [38]

Study selection followed explicit inclusion and exclusion criteria. Publications were retained when they reported experimental data, process modeling, technoeconomic analysis, lifecycle assessment, or pilot-scale evidence that could inform comparison across capture routes. Screening proceeded in three stages: abstract filtering for topical relevance, full-text review for methodological sufficiency, and structured extraction of quantitative and qualitative information. Studies that repeated prior reviews without adding analytical value, or that lacked reproducible detail, were excluded from the final synthesis.

Table 1. Literature screening and selection criteria

Stage	Description	Outcome	Stage
Abstract screening	Initial relevance check based on keywords and research focus	2,500 articles shortlisted	Abstract screening
Full-text screening	Evaluation of methodological soundness and originality	1,200 articles retained	Full-text screening
Data extraction	Structured extraction of performance, cost, and LCA metrics	650 articles included	Data extraction

A central objective of the methodology was to compare technologies on a common basis despite differences in feed composition and operating environment. [39], [40], [41], [42] To do this, the review extracted capture efficiency, regeneration energy, working capacity, heat of adsorption, cyclic durability, permeability, selectivity, and cost indicators wherever available. [43], [44], [45] Route-specific metrics were also retained when essential: solvent degradation and corrosion for absorption systems, breakthrough behavior and diffusion resistance for adsorption systems, module durability for membranes, and refrigeration demand and purity for cryogenic separation. [46], [47], [48]

To improve reproducibility, the extracted studies were grouped by capture pathway, material family, process configuration, and technology readiness level. Reported values were normalized where possible and interpreted as ranges rather than single-point truths, since many studies use different test conditions, impurities, and boundary assumptions. This database-style approach enabled trend recognition across time, highlighted where consensus exists, and prevented isolated best-case results from dominating the overall interpretation.

Table 2. Key performance indicators for carbon capture technologies

Technology	Primary Metrics	Typical Range	Technology
Absorption (MEA-based)	Capture efficiency (%), regeneration energy (GJ/tCO_2)	85–95%; 3.0–4.0	Absorption (MEA-based)

Adsorption (MOFs, zeolites)	Capacity (mmol/g), heat of adsorption (kJ/mol)	2–6; 20–50	Adsorption (MOFs, zeolites)
Membranes	Selectivity (CO_2/N_2), permeability (Barrer)	30–200; 100–1000	Membranes
Cryogenic separation	CO_2 purity (%), refrigeration demand (kWh/tCO_2)	95–99; 250–400	Cryogenic separation

Technoeconomic and environmental information was treated using harmonized boundaries as far as the literature allowed. [49], [50], [51] Cost values were interpreted on a normalized currency-year basis, while lifecycle evidence was examined from material production through capture, regeneration, compression, and either utilization or storage. [52], [53], [54] The review also considered how capture units interact with host systems such as NGCC plants, coal-fired units, industrial facilities, and ambient-air systems, because integration strongly influences both cost and net climate benefit. [55], [56], [57]

Methodological robustness was strengthened through triangulation between experimental studies, simulation-based analyses, technoeconomic models, and field demonstrations. Sensitivity studies were used to understand the effect of humidity, temperature, flue-gas composition, electricity price, and regeneration conditions on reported performance. Pilot and demonstration projects were not treated as anecdotal add-ons; instead, they were used to test whether laboratory and model claims remain credible when exposed to operational realities such as downtime, material aging, financing constraints, and public acceptance.

Finally, the review deliberately incorporated broader deployment considerations, including land and water demand, solvent or sorbent losses, transport and storage availability, and regional equity concerns. This broader framing was necessary because a technically strong capture option may still prove weak once environmental burden, infrastructure dependency, or social acceptance is accounted for. The methodology therefore links scientific performance with implementation realism rather than treating them as separate conversations.

Table 3. Technoeconomic benchmarks (normalized to 2023 USD)

Capture Route	Cost (USD/tCO_2)	TRL
Post-combustion (amine scrubbing)	40–120	8–9
Pre-combustion (shift + separation)	20–70	7–8
Oxy-fuel combustion	50–100	6–7
Direct Air Capture (DAC)	200–600	4–6

3. Results

The reviewed literature portrays carbon capture as a fast-diversifying field in which mature solvent systems, advanced solid sorbents, membranes, cryogenic approaches, and DAC are increasingly positioned for different roles rather than direct one-to-one competition. [58], [59], [60], [61] Across this portfolio, performance is determined not only by intrinsic material properties but also by process design, regeneration strategy, impurity tolerance, and system integration. [62], [63], [64], [65] A recurring conclusion is that the most effective pathway depends on application context rather than on a single headline metric. [66], [67], [68]

Benchmark evidence continues to show that post-combustion amine absorption is the most operationally mature route, regularly exceeding 90% capture under controlled conditions, albeit at a substantial regeneration-energy penalty. Adsorption systems offer a broader design space: zeolites remain strong low-cost performers under dry conditions, while amine-functionalized silicas, polymer amines, and selected MOFs can deliver higher selectivity or capacity under dilute CO_2 streams. Membranes and cryogenic units occupy more specialized niches, but their value increases when purity, compactness, or integration with existing pressure infrastructure matters.

The cost envelope remains one of the clearest separators between routes. Pre-combustion processes typically occupy the lowest literature-reported range, followed by post-combustion and oxy-fuel systems, while DAC remains distinctly more expensive because of the very low CO_2 partial pressure in ambient air. Figure 1 reframes these literature ranges as an interval plot, making the widening spread from conventional capture toward DAC immediately visible.

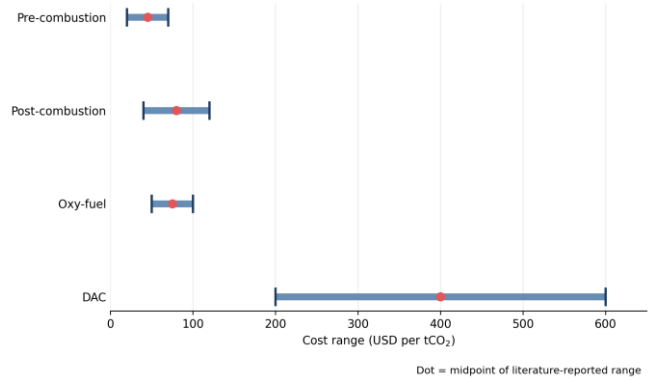

Fig. 1. Interval plot of literature-reported cost ranges for major carbon capture routes.

A regional reading of the literature reveals different strategic priorities. Europe and North America still emphasize retrofit-oriented post-combustion capture, while Asia shows strong momentum in adsorption and membrane deployment for steel, cement, and broader industrial sectors. In the Middle East, DAC and renewable-coupled capture concepts are increasingly prominent because abundant solar resources and emerging carbon-management infrastructure alter the usual energy penalty calculations.

Environmental conditions repeatedly emerge as a first-order determinant of performance. [69], [70], [71] Humidity, temperature, flue-gas contaminants, and cycle severity all influence material stability and process productivity. [72], [73] Systems that appear highly competitive under ideal dry-gas screening can lose that advantage under realistic humid operation, especially for moisture-sensitive physisorbents and membranes. [74], [75] This makes field robustness as important as laboratory peak performance. [76], [77]

Hybridization is one response to that complexity. Studies that combine absorption with adsorption, or membranes with cryogenic polishing, show that staged architectures can shift duties toward the unit operation best suited to each step, thereby reducing overall energy use and improving flexibility. The literature also points toward process integration as a critical design principle rather than an afterthought.

Structured contactors strengthen this trend by attacking transport limitations directly. Monoliths, fibers, and 3D-printed lattice sorbents reduce pressure drop and shorten diffusion paths, which can improve dynamic performance even when equilibrium capacity is not the highest in the material set. These geometries matter because industrial viability depends on throughput and cycle productivity as much as on static uptake.

Dynamic testing reinforces that point. Breakthrough behavior remains one of the most informative ways to compare solid sorbents because it combines kinetics, working capacity, and competitive adsorption into a single observable response. Zeolites often show sharp fronts and strong dry-gas affinity, activated carbons favor moisture tolerance and stability, while amine-bearing solids tend to provide smoother but more resilient performance under dilute or humid conditions.

MOF-based systems illustrate both the promise and the present limitation of advanced adsorbents. Under optimized dry conditions, materials such as Mg-MOF-74 can outperform conventional solids, yet long-term humidity resistance, mechanical durability, and manufacturing cost remain unresolved for many candidates. Functional coatings and framework modifications have improved survivability, but the gap between laboratory novelty and deployable material quality is still substantial.

Instead of repeating breakthrough curves, Figure 2 summarizes the literature qualitatively as a heatmap across dry capacity, humidity tolerance, kinetics, cyclic stability, and scale readiness. This format better captures the fact that deployment decisions are multi-criteria decisions, not single-metric rankings.

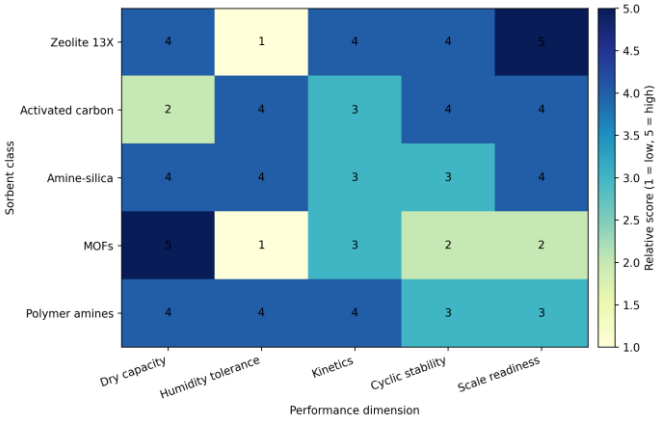

Fig. 2. Comparative heatmap of major sorbent classes across key performance dimensions.

The dynamic evidence also shows that high equilibrium uptake alone is an incomplete indicator of process quality. Fast adsorption and desorption, limited diffusion resistance, and stable cycling can outweigh a modest sacrifice in maximum capacity, particularly in PSA, TSA, or VSA systems with short cycles. In that sense, transport engineering and contactor design deserve the same emphasis as sorbent chemistry.

Pilot-scale adsorption results support this interpretation. Amine-silica units operating near the 1 t day^{-1} scale have shown hundreds to thousands of cycles with competitive regeneration duties, while activated carbon systems have demonstrated resilience to fluctuating flue-gas composition even when their absolute capture efficiency is lower. These results suggest that scalability is governed by stability and maintainability as much as by headline capacity.

The literature nevertheless remains difficult to compare directly because test protocols vary widely in flow rate, CO_2 concentration, humidity, and regeneration procedure. Standardized screening and reporting frameworks are therefore essential if materials are to be compared fairly across research groups and moved efficiently toward qualification for pilot use.

Regeneration behavior is equally decisive for long-term economics. Thermal degradation, oxidative aging, incomplete desorption, and vacuum limitations all reshape the apparent value of a material once repeated operation is considered. Low-temperature regeneration, steam assistance, and other intensified approaches are promising, but the literature makes clear that stability and regeneration cannot be optimized independently.

Comparable lessons appear in membrane and cryogenic studies. Polymeric membranes may report attractive selectivity in clean-gas tests, yet real flue-gas contaminants can erode performance over time; mixed-matrix designs improve this picture but introduce manufacturing complexity. Cryogenic routes remain more limited in use, but they are notable where very high CO_2 purity is required or where refrigeration infrastructure already exists.

Taken together, the dynamic and equilibrium evidence shows that carbon capture materials must be judged holistically. A viable material is not simply one with high uptake, but one that remains productive, regenerable, and tolerant to the environment in which it will actually operate.

Technoeconomic findings add a second layer to this comparison. Reported capture costs are shaped by energy duty, equipment scale, material replacement, and financing structure, but energy consumption remains the dominant driver in most studies. This is why regeneration strategy, heat integration, and electricity source appear repeatedly as decisive variables across otherwise different capture routes.

CAPEX and OPEX contributions vary by technology. Conventional amine systems are heavily influenced by absorbers, strippers, and heat exchangers, whereas adsorption routes shift some of that cost toward solid-contacting hardware, vacuum systems, or structured modules. In DAC, modular air contactors and regeneration units amplify the capital share, especially at early deployment stages.

Figure 3 replaces the earlier pie chart with a stacked comparison across representative technology classes. The visual emphasizes that energy penalty is consistently the largest contributor, but also shows that the balance between capital and operating costs changes as systems move from mature point-source capture toward DAC.

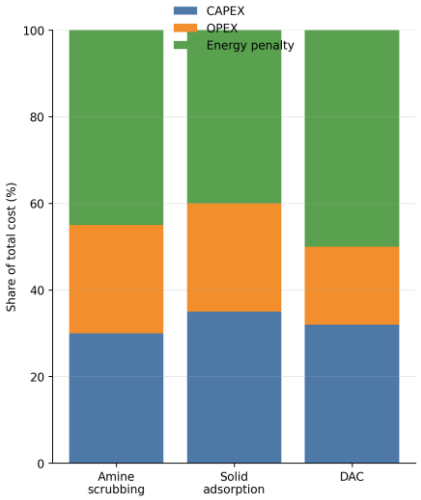

Fig. 3. Stacked comparison of indicative CAPEX, OPEX, and energy-penalty contributions.

The dominance of energy cost explains why solvent and sorbent selection cannot be separated from system integration. Biphasic solvents, improved heat recovery, low-temperature desorption, microwave-assisted regeneration, and renewable electricity supply all appear in the literature as routes to meaningful cost reduction. In many cases, the economic advantage comes less from a single material breakthrough than from reducing the effective cost of the regeneration step.

Location and sector matter as well. Capture tends to be more favorable where electricity is cheap or low carbon and where flue-gas CO_2 concentration is relatively high, as in some industrial streams. Conversely, dilute streams and carbon-intensive power inputs can narrow or even negate the apparent climate advantage of a capture installation.

Learning effects remain an important source of optimism. Demonstration data and forward-looking models suggest that costs can fall substantially with cumulative deployment, standardization, and plant-to-plant learning. The implication is not that cost reduction is automatic, but that early deployment has a strategic value because it builds the experience base required for later cost decline.

Lifecycle assessment adds discipline to the technoeconomic narrative. High point-capture efficiency does not always translate into equally high net climate benefit once electricity use, sorbent manufacture, construction, and transport are included. The strongest lifecycle outcomes are consistently associated with low-carbon energy supply and credible downstream storage or utilization pathways.

Real projects illustrate this gap between modeled potential and field performance. Petra Nova, Boundary Dam, and early DAC facilities have all provided invaluable operational evidence, but they also show how financing, downtime, parasitic load, and infrastructure dependencies can widen the gap between headline performance and delivered economics.

Policy support therefore becomes part of the results rather than just contextual background. Incentives such as the U.S. 45Q tax credit, emissions-trading mechanisms, and industrial decarbonization programs materially change project bankability and deployment timing. The literature repeatedly shows that technically sound systems often stall without predictable policy support.

Overall, the technoeconomic evidence points toward targeted rather than universal deployment. Capture is most compelling when energy supply, infrastructure access, and source characteristics are aligned; it is

least compelling when high separation work is paired with expensive or carbon-intensive energy.

System integration is where these strands converge. [78], [79], [80] The literature consistently shows that stand-alone capture units underperform integrated configurations in which heat, pressure, electricity, and CO_2 handling are deliberately co-optimized. [81], [82], [83] In practice, this means that host-facility coupling is often as important as the choice of capture chemistry. [84], [85]

For absorption systems, the most common integration benefit is waste-heat recovery for solvent regeneration. For adsorption units, access to low-grade thermal energy or flexible renewable power can materially reduce regeneration cost. Membranes benefit from existing compression infrastructure, while DAC tends to gain most when colocated with renewable-energy hubs or storage-ready carbon-management clusters.

Hybrid configurations extend this systems logic. Solvent stages can perform bulk separation, solid sorbents can act as polishing steps, and membranes can reduce the duty of downstream cryogenic or compression units. Literature models suggest that such combinations can lower total cost and improve operating flexibility, provided that control strategies and mass-integration choices are designed coherently.

Figure 4 summarizes these relationships as a bubble matrix rather than as a simple process sketch. The goal is to show which capture routes align most strongly with waste heat, low-temperature heat, renewable electricity, CO_2 cluster infrastructure, and utilization pathways.

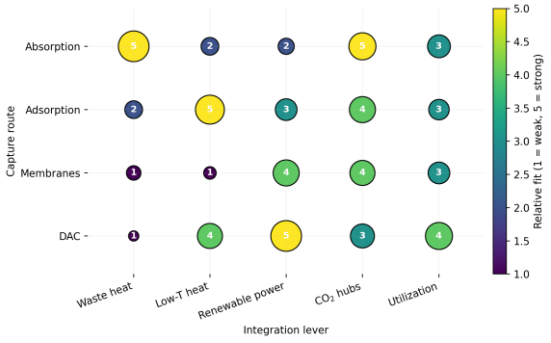

Fig. 4. Relative integration fit of major capture routes with key infrastructure and energy levers.

Integration also has a spatial dimension. Shared transport corridors, compression hubs, and storage reservoirs can reduce the cost burden of individual projects and raise utilization factors for common infrastructure. This is particularly important for industrial clusters, where no single emitter may justify a full stand-alone CO_2 network on its own.

Digital monitoring and advanced control further reinforce integrated performance. Dynamic optimization can align capture duty with plant load, renewable availability, and downstream storage conditions, reducing unnecessary regeneration and improving system responsiveness. These tools matter most in systems that must operate flexibly rather than at a fixed base load.

Case studies from power, industry, and DAC deployment confirm that integration benefits are real but not automatic. Projects linked to reliable low-carbon heat or power and to credible storage pathways generally achieve better net performance than technically similar systems developed in isolation.

Integration also improves environmental performance by reducing duplicate infrastructure and lowering indirect energy use. When coupled with flue-gas cleaning, renewable inputs, or shared storage networks, capture systems can deliver co-benefits beyond CO_2 abatement, including reduced local pollutant exposure and better resource efficiency.

The principal result of the integration literature is therefore conceptual as well as numerical: carbon capture functions best as part of a broader carbon-management architecture, not as a bolt-on addendum.

Environmental sensitivity is especially visible in adsorption-based systems. Across experimental and modeling studies, temperature and humidity alter not only equilibrium uptake but also cycle time, bed utilization, and regeneration severity. This is why climate-specific evaluation is indispensable, especially for DAC and for humid flue-gas treatment.

The literature synthesis indicates that zeolite 13X can lose a large fraction of its dry-gas working capacity as relative humidity rises, whereas activated carbons and several amine-bearing solids retain performance more effectively under moisture exposure, albeit often at lower absolute uptake or with different regeneration burdens. The main lesson is that sorbent ranking can invert once humidity is introduced.

Figure 5 converts that message into a contour map of normalized uptake over temperature and relative humidity. The figure is not intended as a universal material law; rather, it visualizes the operational envelope implied by the literature, in which warmer and wetter conditions progressively erode capture performance.

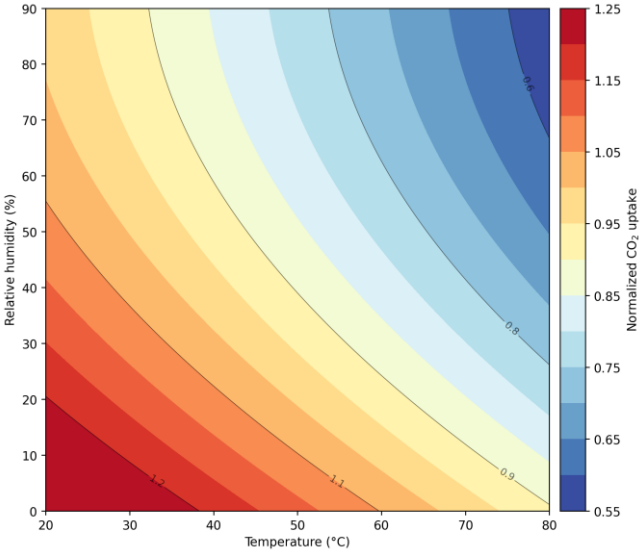

Fig. 5. Contour map of normalized CO_2 uptake under coupled temperature-humidity variation.

These climate effects have direct design implications. In humid environments, front-end dehumidification, hydrophobic surface modification, or the selection of moisture-tolerant sorbents becomes more important. In hot climates, heat management and regeneration strategy become even more tightly coupled because reduced adsorption capacity and higher desorption duty can occur simultaneously.

Kinetics are also climate sensitive. Water can block access to active sites, slow diffusion through pore networks, and broaden breakthrough fronts, thereby reducing bed productivity even when some equilibrium capacity is retained. These kinetic penalties matter in real equipment because they increase contactor size or shorten cycle efficiency.

Structured adsorbents mitigate part of this penalty by shortening transport paths and improving heat removal. CFD studies and reactor-scale experiments suggest that monoliths, laminates, and open lattice geometries can preserve more usable capacity under adverse conditions than randomly packed beds with otherwise similar chemistry.

Field observations reinforce the modeling results. Systems tested in humid climates or under highly variable operating conditions commonly report lower capture efficiency than dry-laboratory projections, unless the design explicitly accounts for moisture management, sorbent aging, and regeneration control.

The economic consequence is straightforward: poor climate matching increases both energy use and replacement cost. Extra drying, deeper vacuum, longer regeneration, or faster sorbent turnover can materially alter the apparent cost advantage of a technology once it is transferred from a screening rig to a real site.

Climate sensitivity also appears in lifecycle metrics. Systems that depend on energy-intensive environmental control or on frequent material replacement can surrender a significant share of their gross CO_2 benefit, which is why local conditions must be treated as part of the technology assessment rather than as a separate deployment issue.

In summary, the environmental-results literature argues against generic performance claims. Capture systems should be evaluated as

climate-conditioned systems whose actual ranking depends on where and how they are expected to operate.

The final stage of carbon capture is not separation itself but the management of the captured CO_2 stream. Once CO_2 has been isolated, its climate value depends on conditioning, transport, utilization, or long-term storage. This downstream chain strongly affects project cost, risk, and permanence.

Compression and transport are among the most mature steps in that chain, yet they are still energy- and infrastructure-intensive. Reaching pipeline-grade pressure adds a nontrivial energy load, and the feasibility of transport depends on distance, throughput, and access to shared networks.

Utilization pathways can improve economics, particularly in fuels, chemicals, and construction materials, but their climate value depends on permanence and substitution effect. Short-lived fuel pathways often recycle carbon rather than permanently remove it, whereas mineralization and durable material incorporation can deliver longer storage horizons.

Geological storage remains the benchmark for permanent large-scale mitigation. Case studies from offshore storage and saline formations confirm technical feasibility, but they also show that public trust, monitoring, regulatory clarity, and long-term liability are central to deployment success.

Figure 6 replaces the earlier flow diagram with a pathway map that links source categories to capture conditioning, compression and transport, and the two main downstream options: utilization and storage. This framing better reflects the network character of real carbon-management systems.

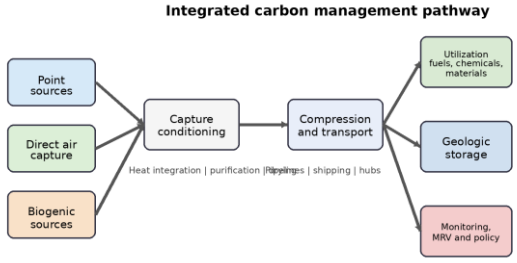

Fig. 6. Pathway map linking CO_2 sources, capture conditioning, transport, utilization, and storage.

Regional deployment pathways are already diverging. North America remains strongly associated with EOR-linked infrastructure, Europe is emphasizing storage-oriented cluster development, and regions with emerging renewable overcapacity are increasingly examining CO_2 use in synthetic-fuel systems. These choices shape both economics and public perception.

Lifecycle evidence confirms that downstream choices matter profoundly. Storage can deliver high permanence, whereas some utilization routes mainly delay re-emission. Consequently, capture pathways that look similar at the separation step may differ substantially in long-term climate benefit once their downstream destination is specified.

Network economics further favor coordinated development. Shared compression assets, pipeline systems, shipping terminals, and storage hubs lower the effective cost of capture for individual projects and reduce the threshold size needed for participation.

Regulation ultimately governs whether these networks materialize. Permitting, monitoring requirements, cross-border transport rules, carbon accounting, and long-duration liability frameworks influence investment decisions as directly as material performance does.

The downstream literature therefore reinforces a central conclusion of this review: capture technologies realize their full mitigation value only when they are embedded in credible CO_2 management systems that connect separation to compression, transport, utilization, or durable storage.

4. Discussion

The results confirm that carbon capture should be treated as a portfolio of technologies whose suitability depends on source concentration, climate, energy availability, infrastructure access, and the required degree of permanence. [3], [5], [6] This portfolio perspective matters because arguments framed around a single 'best' capture option often ignore the contextual variables that actually determine performance in practice. [52], [7]

From a materials standpoint, the literature does not support a universal winner. Zeolites remain attractive because they are inexpensive and mature, activated carbons offer resilience, amine-bearing solids perform well under dilute or humid conditions, and MOFs continue to define the upper edge of tunability and dry-condition performance. The choice among them is therefore a systems decision, not merely a materials decision.

The technoeconomic evidence leads to the same conclusion. Lower nominal cost does not automatically imply stronger deployment value, because the energy source, regeneration strategy, plant integration, and downstream CO_2 pathway can shift both economics and lifecycle emissions materially. For this reason, capture costs should be interpreted as scenario-dependent ranges rather than universal benchmarks.

Integration emerges as the strongest cross-cutting theme in the discussion. Whether the system uses waste heat, low-grade heat, flexible electricity, shared transport and storage, or hybrid separation trains, integrated designs consistently outperform isolated ones. This suggests that future progress will depend as much on plant architecture and infrastructure planning as on the invention of new capture media.

The environmental results also add an important caution. Capture technologies can deliver very high gross removal or avoidance efficiencies, but poor energy sourcing, moisture sensitivity, or weak downstream permanence can reduce net benefit significantly. In other words, the climate value of capture depends on the full chain from separation through final CO_2 disposition.

Downstream management is therefore not peripheral to the carbon-capture discussion. Without reliable compression, transport, and storage or genuinely beneficial utilization, the capture step risks becoming an isolated intermediate operation rather than a complete mitigation solution. The literature strongly favors storage-backed systems for deep decarbonization, even when utilization improves project economics in the short term.

Policy and governance complete this picture. Stable incentives, transparent accounting, monitoring frameworks, and clear long-term liability rules determine whether technically credible projects advance to deployment. The field is now mature enough that governance quality is a first-order variable, not a background consideration.

Taken together, the evidence positions carbon capture as both a near-term decarbonization tool and a longer-term enabler of negative-emission strategies. [1], [22], [23], [24], [25], [26] Point-source capture is especially important for hard-to-abate industries in the coming decade, while DAC and other dilute-stream approaches are likely to become more important as residual emissions dominate the remaining mitigation gap. [27], [28], [29], [30], [31]

The future trajectory of the field will therefore be defined by convergence: convergence between materials science and process design, between capture units and energy systems, and between technology deployment and durable CO_2 management infrastructure. Progress in only one of these domains will not be enough.

5. Conclusion

This review shows that carbon capture has progressed from a largely point-source separation technology into a much broader carbon-management field spanning industrial capture, advanced sorbents, membranes, DAC, and integrated CO_2 networks. [11], [13], [14] The strongest current pathways combine technical maturity with system-level compatibility rather than maximizing a single laboratory metric. [16], [28]

The comparative evidence indicates that capture performance is shaped by four coupled determinants: the intrinsic behavior of the capture medium, the regeneration burden, the quality of process integration, and

the downstream fate of the CO_2 stream. [58], [60], [24] Routes that align these factors well can deliver strong mitigation value; routes that do not may struggle despite promising isolated metrics. [74], [27], [79]

In deployment terms, the literature supports a dual strategy. [1], [2], [6] Established point-source capture should continue where it can address hard-to-abate emissions efficiently, while advanced solids, hybrid systems, and DAC should be developed where they offer strategic advantages in flexibility, modularity, or negative-emission potential. [56], [8], [9]

Ultimately, scaling carbon capture will require coordinated advances in materials development, intensified process design, low-carbon energy supply, transport and storage infrastructure, and durable policy support. [7], [57], [80] When these elements move together, carbon capture can serve as a consequential pillar of climate mitigation rather than a supplementary option. [81], [31], [10]

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