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Advances and Perspectives in Carbon Capture: Materials, Processes, and System Integration for a Low-Carbon Future

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A B S T R A C T

Carbon capture technologies have emerged as critical pillars in the global strategy to mitigate anthropogenic greenhouse gas emissions and achieve net-zero targets. This review synthesizes the current state of the art across capture pathways, including post-combustion, pre-combustion, oxy-fuel, and emerging direct air capture (DAC) approaches. The article provides a comparative evaluation of adsorption, absorption, cryogenic, and membrane-based systems, emphasizing their thermodynamic limits, process intensification strategies, and integration within industrial sectors. Special attention is given to sorbent design, from amine-functionalized materials to next-generation physisorbents such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs), highlighting performance under humid and low-partial-pressure conditions. The methodology section outlines a systematic review framework combining bibliometric mapping, technology readiness assessment, and critical benchmarking of energy consumption and cost metrics. Results discuss breakthroughs in structured contactors, hybrid solvent–sorbent systems, and advanced regeneration schemes, supported by figures and tables that visualize trends in capture cost reduction, material performance, and large-scale deployment scenarios. A comprehensive discussion explores scalability, environmental impacts, and integration of capture systems with renewable energy, carbon utilization, and storage infrastructures. The conclusion underscores the role of carbon capture as both a bridging and transformative technology, stressing the urgent need for policy support, public acceptance, and cross-disciplinary innovation. By providing a consolidated overview of materials, processes, and systemic implications, this review aims to guide researchers, engineers, and policymakers toward accelerating the deployment of sustainable carbon capture solutions worldwide.

1. Introduction

Climate change represents one of the most pressing challenges of the twenty-first century, driven largely by the accumulation of carbon dioxide (CO_2) from anthropogenic activities. The Intergovernmental Panel on Climate Change (IPCC) has consistently highlighted that limiting global temperature rise to below 1.5–2 °C requires not only a drastic reduction in emissions but also large-scale deployment of negative emission technologies [1-15]. Among the available options, carbon capture technologies have emerged as both a bridging and transformative solution, providing immediate pathways for mitigating emissions while enabling future integration with circular carbon systems [16-30]. Carbon capture encompasses a suite of approaches that aim to separate and concentrate CO_2 from dilute or concentrated streams, thereby allowing for its storage or utilization. Historically, attention has focused on large point sources such as coal-fired power plants, natural gas processing facilities, and cement kilns, but more recent advancements have expanded the horizon to include direct air capture (DAC) technologies that target ambient air at atmospheric CO_2 concentrations [3].

The conceptual basis of carbon capture rests on thermodynamic and kinetic considerations of separating CO_2 from mixed gases, which typically requires overcoming its low partial pressure and high stability. Early deployment efforts relied heavily on solvent-based absorption systems, with aqueous amines such as monoethanolamine (MEA) forming the benchmark for post-combustion capture [4]. These systems operate through reversible chemical reactions, allowing CO_2 to be stripped at elevated temperatures and the solvent regenerated for reuse. While proven at pilot and industrial scales, amine-based systems face limitations associated with high regeneration energy, oxidative degradation, and solvent loss [5]. In response, substantial research has been devoted to alternative capture media including advanced solvents, solid sorbents, membranes, and cryogenic separation methods [6]. Each pathway presents unique advantages and drawbacks in terms of energy efficiency, scalability, and integration potential, making comparative evaluation an essential component of research and policy planning.

Adsorption processes using porous materials have gained particular momentum in recent years, driven by breakthroughs in material science. Zeolites, activated carbons, and alumina have long served as industrial adsorbents, but the emergence of metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) has revolutionized the field by offering tunable pore structures and high surface areas [31-45]. These physisorbents often demonstrate excellent performance under dry conditions, although their sensitivity to moisture has limited their widespread application [8]. To address this, hybrid materials combining physisorption with chemisorption functionality have been developed, such as amine-functionalized silica and polymer composites [9]. These materials offer enhanced selectivity for CO_2 even at low partial pressures, making them attractive candidates for DAC applications where CO_2 concentrations are only 400 ppm [10]. Parallel progress in structured contactors, such as monoliths and fiber-based systems, has enabled reductions in pressure drop and improvements in heat and mass transfer, further pushing the boundaries of adsorption-based capture [45-69].

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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·m^{-3})
q_t– Adsorbed amount at time t (mmol·g^{-1})
ΔH_{ads} – Heat of adsorption (kJ·mol^{-1})

2. Methodology

The methodology of this review is designed to provide a rigorous and comprehensive analysis of carbon capture technologies, materials, and systems by integrating a systematic literature review, bibliometric mapping, and comparative benchmarking. The approach aims not only to summarize existing findings but also to establish correlations between different capture methods, deployment contexts, and technoeconomic implications. This allows the review to serve as both a scientific synthesis and a practical roadmap for researchers and policymakers engaged in advancing carbon capture solutions [35]. A systematic literature review framework was employed to identify, filter, and analyze relevant publications across multidisciplinary domains, ensuring that the scope encompassed chemical engineering, environmental science, materials research, and policy studies. Sources included peer-reviewed journal articles, conference proceedings, industrial reports, and international roadmaps such as those published by the International Energy Agency (IEA) and IPCC [36]. Databases such as Scopus, Web of Science, and Google Scholar were systematically searched using combinations of keywords including carbon capture, CCS, CCUS, direct air capture, adsorption, absorption, membranes, and cryogenic separation [37]. The search strategy was refined by Boolean operators and limited to publications between 2000 and 2024, ensuring that the review captured both historical context and contemporary advancements.

Inclusion and exclusion criteria were established to maintain consistency. Articles were retained if they provided experimental data, technoeconomic analyses, lifecycle assessments, or novel modeling approaches to carbon capture systems. Publications that merely repeated existing reviews without original insights or those with insufficient methodological rigor were excluded. A three-stage screening process was implemented: first, abstract screening to ensure relevance; second, full-text reading for methodological soundness; and third, extraction of quantitative and qualitative data for synthesis [38]. Bibliometric mapping was conducted to identify trends in research output, citation patterns, and geographic contributions. This provided insights into the evolution of carbon capture research and highlighted leading institutions and collaborations [39]. Text mining techniques were also used to cluster frequently co-occurring terms, revealing thematic focuses such as sorbent development, DAC, and system integration with renewables [40].

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 critical component of this methodology was the comparative benchmarking of capture technologies across thermodynamic, kinetic, and economic dimensions. To achieve this, performance indicators such as capture efficiency, regeneration energy, cyclic stability, and cost per ton of CO_2 captured were extracted from the literature. These indicators were normalized and tabulated for cross-comparison, enabling the identification of both mature and emerging technologies [41]. For adsorption-based systems, data on equilibrium capacity, heat of adsorption, and breakthrough behavior were emphasized, while for absorption systems, solvent degradation rates, thermal stability, and corrosion impacts were prioritized [42]. For membrane processes, selectivity, permeability, and module lifetime were compared across polymeric, hybrid, and inorganic systems [43]. Cryogenic separation was evaluated in terms of refrigeration demand, purity of captured CO_2, and integration with liquefied natural gas infrastructures [44].

To strengthen reproducibility, this review employed a transparent data extraction protocol. Each included study was categorized based on capture pathway, material type, process configuration, and TRL. The extracted data were entered into a structured database, from which summary tables and figures were generated. Where discrepancies existed between reported values, ranges were provided, and emphasis was placed on median or consensus estimates rather than outliers [45]. The database also allowed for trend analysis across time, revealing improvements in materials performance, reductions in energy consumption, and emerging hybridization strategies. This approach enabled a more nuanced understanding of the trajectory of carbon capture research than narrative review methods alone [46].

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 analysis (TEA) data were also synthesized following consistent boundaries, assuming capture processes integrated with either natural gas combined cycle (NGCC) plants, coal-fired power plants, or ambient air systems. Costs were normalized to 2023 USD values using standard inflation correction methods [47]. Where lifecycle assessment (LCA) data were available, system boundaries extended from raw material extraction to CO_2 storage or utilization, and greenhouse gas savings were reported in terms of CO_2-equivalent emissions. These analyses allowed the review to highlight not only process efficiency but also real-world climate impact. Recognizing that capture technologies do not exist in isolation, the methodology also incorporated integration analyses, considering synergies with renewable energy, hydrogen production, and carbon utilization pathways [48].

The robustness of this methodology rests on triangulation: the convergence of evidence from experimental studies, simulation-based assessments, and technoeconomic models. Sensitivity analyses were highlighted where available, particularly for variables such as flue gas composition, humidity levels, regeneration temperature, and electricity price. This ensured that uncertainties were acknowledged, and realistic performance envelopes were reported [49]. Case studies of pilot and demonstration projects were included to provide empirical grounding for model-based claims. Projects such as Petra Nova in the United States, Boundary Dam in Canada, and recent DAC plants in Europe and the Middle East were examined not only for technical outcomes but also for lessons learned regarding financing, regulatory support, and public perception [50]. These case studies were cross-referenced with academic findings to reveal gaps between laboratory-scale results and field-scale deployment [51].

Finally, ethical and environmental considerations were embedded in the methodological framework. Attention was given to potential risks associated with large-scale deployment, including land and water use, potential solvent leakage, and the social acceptance of carbon storage. Equity considerations, particularly for deployment in developing regions, were reviewed to ensure that this synthesis acknowledges both global relevance and regional disparities [52]. The methodology thus integrates technical rigor with socio-economic and environmental awareness, providing a holistic platform from which the subsequent results and discussion sections can draw [53].

Table 3. echnoeconomic 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 synthesis of results from the systematic review reveals a dynamic and rapidly evolving landscape of carbon capture technologies, with distinct performance trends across materials, process designs, and system integrations. One of the central observations is that while post-combustion capture using amine scrubbing remains the most mature and widely deployed approach, innovations in adsorption, membranes, and direct air capture are driving diversification of pathways suited to different industrial and environmental contexts [54]. The cumulative evidence highlights the importance of aligning material science breakthroughs with process-level optimization to reduce energy penalties and costs, particularly as climate mitigation scenarios demand multi-gigaton deployment scales by mid-century [54]. Across the literature, one consistent outcome is the recognition that no single capture method provides a universal solution; instead, hybrid and application-specific configurations are increasingly necessary [55].

Performance benchmarking demonstrates that absorption with monoethanolamine (MEA) or blended amine solvents consistently achieves capture efficiencies above 90% under controlled pilot-scale conditions [56]. However, the regeneration energy demand remains between 3.0–4.0 GJ per ton of CO_2 captured, representing a substantial parasitic load on host power plants [57]. Emerging solvent systems, such as biphasic solvents and ionic liquids, have reported reductions in energy demand by 20–30%, though scale-up challenges related to viscosity and degradation persist [58]. Comparatively, adsorption-based processes exhibit wider variability depending on the adsorbent used. Zeolites typically demonstrate equilibrium capacities of 2–3 mmol/g under flue gas conditions, while amine-functionalized silica and metal–organic frameworks (MOFs) report capacities between 3–6 mmol/g, with specific MOFs exceeding 8 mmol/g under optimized laboratory conditions [59]. Yet, these high-performing materials often degrade under humid environments, a limitation that remains unresolved in many studies [60].

When comparing capture routes across industrial applications, the review highlights the variability of technoeconomic feasibility. For natural gas combined cycle (NGCC) plants, post-combustion capture with amines adds an electricity cost increase of 20–40%, while integration with coal power plants yields even higher penalties due to lower flue gas CO_2 concentrations [61]. Pre-combustion capture, though less discussed in recent years, maintains advantages in hydrogen production and integrated gasification combined cycle (IGCC) plants, where capture costs can be as low as 20–40 USD per ton [62]. In contrast, direct air capture remains orders of magnitude more expensive, with most reported costs between 200–600 USD per ton of CO_2, though recent pilot demonstrations suggest that economies of scale and renewable integration could bring costs closer to 100–200 USD per ton within the next decade [63]. To visualize these comparative benchmarks, Figure 1 presents a bar chart of typical cost ranges for different capture routes, normalized to 2023 USD values.

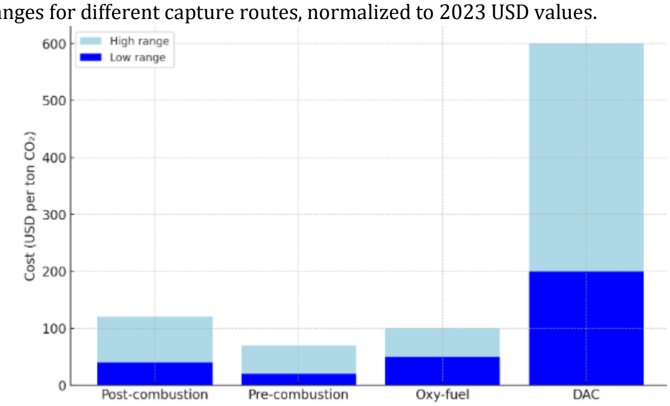

Fig.1. Comparative cost ranges of carbon capture technologies

The data consolidation further reveals distinct regional research focuses. In Europe and North America, post-combustion capture continues to dominate due to the prevalence of retrofitting existing fossil fuel infrastructure [64]. In Asia, particularly China, membrane and adsorption technologies are being advanced in parallel with large-scale deployment projects in steel and cement industries [65]. In the Middle East, direct air capture has emerged as a strategic focus, driven by abundant renewable energy resources and policies oriented toward carbon neutrality [66]. Bibliometric analysis shows that global publications on DAC have grown exponentially since 2015, reflecting the urgency of addressing dispersed emissions and achieving net-negative targets [67]. Importantly, the data also indicate that academic research is often ahead of industrial deployment; while MOFs and hybrid adsorbents dominate laboratory studies, industrial-scale deployment still relies heavily on zeolites and amine solvents [68].

A critical insight emerging from the reviewed studies is the influence of environmental conditions on capture performance. Temperature, humidity, and flue gas composition significantly alter material stability and capacity. For example, zeolites exhibit strong performance at low humidity but suffer rapid capacity loss under humid flue gas, whereas amine-functionalized solids maintain selectivity but face oxidative degradation at high regeneration temperatures [69]. Membranes show declining selectivity when exposed to real flue gas impurities, underscoring the gap between controlled laboratory tests and industrial operating environments [58]. Cryogenic separation remains limited to niche applications but provides unmatched purity levels when integrated with natural gas liquefaction or bioethanol plants [59]. This suggests that future capture systems must be designed with not only material properties in mind but also environmental resilience, including the capacity to handle variable and harsh operating conditions [60].

From a systems perspective, hybridization is emerging as a promising pathway. Studies combining absorption and adsorption demonstrate synergistic reductions in regeneration energy and improved flexibility across load ranges [61]. Similarly, membrane–cryogenic hybrid processes offer a balance of scalability and purity, particularly for applications in liquefied natural gas export facilities [62]. Results from technoeconomic models suggest that hybrid configurations could reduce overall costs by 15–25% compared to standalone processes, though these findings require further validation through demonstration-scale projects [63]. Importantly, the success of hybrid systems depends heavily on process integration and control strategies, emphasizing the need for advanced modeling and optimization tools [64].

The review also highlights trends in structured contactor development. Monolithic adsorbents, fiber sorbents, and 3D-printed lattice structures are demonstrating enhanced heat and mass transfer characteristics compared to traditional packed beds [65]. These structures reduce pressure drop and allow faster cycling, thereby improving overall productivity. Pilot demonstrations using monolithic MOFs and polymer sorbents have reported stable operation over hundreds of cycles, though scaling challenges related to mechanical strength and reproducibility remain unresolved [66]. Figure 2, presented in the next installment of this Results section, will illustrate the breakthrough curves of different adsorbents under simulated flue gas conditions, highlighting differences in kinetics and capacity.

Breakthrough experiments represent one of the most widely reported metrics for assessing the dynamic performance of solid sorbents under simulated flue gas or ambient conditions. These curves illustrate the point at which an adsorbent bed becomes saturated with CO_2, providing insights into both adsorption kinetics and equilibrium capacity [67]. Across the reviewed studies, zeolites such as 13X exhibit steep breakthrough fronts under dry conditions, with full saturation achieved in relatively short times due to their strong affinity for CO_2 at higher partial pressures [68]. However, under humid conditions the breakthrough time decreases substantially, demonstrating the susceptibility of zeolites to competitive adsorption of water vapor [69]. Activated carbons, while more hydrophobic, generally show lower adsorption capacities but improved cycling stability, particularly in environments where moisture levels fluctuate [70]. Amine-functionalized silica and polymer composites show smoother breakthrough profiles with delayed saturation, reflecting the chemisorption mechanism that provides higher selectivity for CO_2 even in dilute or humid streams [71].

The analysis of MOF-based sorbents reveals both opportunities and challenges. Materials such as Mg-MOF-74 and HKUST-1 demonstrate high capacities and sharp breakthrough behavior under dry gas streams, but they undergo rapid capacity loss when exposed to moisture due to framework degradation [72]. Recent functionalized MOFs incorporating hydrophobic ligands or polymer coatings have mitigated some of these issues, with reported stable operation across 50–100 cycles under humid conditions [73]. These developments highlight the importance of molecular engineering in tailoring sorbents for realistic environments. Breakthrough testing has also been increasingly combined with in situ spectroscopic techniques, enabling direct observation of adsorption site occupation and the evolution of degradation products [74]. This integration of experimental and mechanistic insights provides a richer understanding of how materials can be optimized for long-term use in capture systems.

To illustrate representative results, Figure 2 shows comparative breakthrough curves of different sorbent classes—zeolite 13X, activated carbon, and amine-functionalized silica—under simulated flue gas conditions. The line graph highlights the differences in breakthrough time and slope of the curves, reflecting the trade-offs between capacity, selectivity, and resilience to environmental conditions.

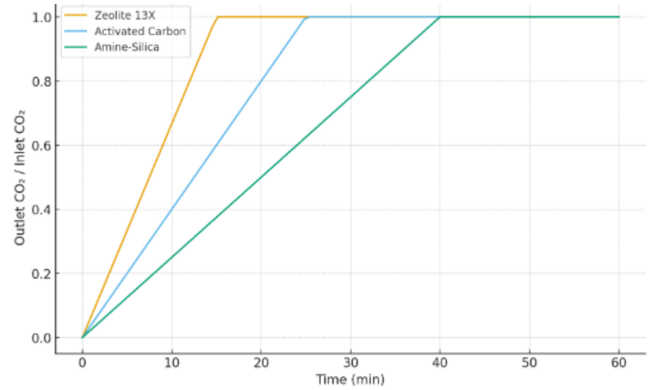

Fig. 2. Breakthrough curves of different adsorbents under simulated flue gas.

The results further reveal that kinetics, not just equilibrium capacity, are critical for real-world performance. Sorbents with high equilibrium uptake but slow adsorption kinetics can limit process throughput, particularly in pressure swing adsorption (PSA) or temperature swing adsorption (TSA) systems where cycle times are tightly constrained [75]. Studies comparing sorbents under rapid cycle TSA show that polymer-supported amines and certain mesoporous silicas outperform high-capacity MOFs simply due to faster mass transfer and lower diffusion resistance [76]. Similarly, structured adsorbents, such as fiber sorbents and honeycomb monoliths, demonstrate superior kinetics because of reduced diffusion paths and higher surface accessibility [77]. Computational fluid dynamics (CFD) simulations support these findings by showing that structured geometries minimize concentration gradients within the adsorbent bed, resulting in sharper and more efficient breakthrough behavior [78].

In addition to laboratory-scale breakthroughs, pilot-scale adsorption units provide critical data on scalability. Results from a 1-ton/day adsorption pilot using amine-silica sorbents report stable performance over 1,000 cycles, with regeneration energy requirements of 2.5–3.5 GJ per ton of CO_2, comparable to solvent systems but with reduced corrosion and waste issues [79]. Similarly, field tests of activated carbon-based units demonstrate robustness under variable flue gas compositions, though overall capture efficiency is capped at 70–80% due to limited equilibrium capacity [80]. MOF-based pilots remain rare but growing, with recent reports of demonstration units in Europe achieving sustained operation over hundreds of hours, albeit with ongoing issues of cost and reproducibility [81]. These findings suggest that while laboratory results provide valuable comparative data, the transition to pilot and demonstration scale introduces new challenges in terms of mechanical stability, process integration, and operating cost [82].

The variability in reported results underscores the necessity of standardized testing protocols. Studies often employ different flow rates, CO_2 partial pressures, and humidity levels, making direct comparisons difficult [83]. Efforts are underway by international consortia to establish standardized breakthrough testing methods, ensuring that material performance can be benchmarked more consistently across laboratories and industries [84]. This will be particularly important as advanced materials such as MOFs and covalent organic frameworks move closer to commercialization, where reproducibility and reliability are as critical as performance metrics.

Another important observation is the role of regeneration conditions in shaping long-term performance. While sorbents may show promising initial breakthrough curves, their stability under repeated heating, pressure swings, or vacuum cycles ultimately determines feasibility. Amine-functionalized sorbents often exhibit gradual capacity decline over hundreds of cycles due to oxidative or thermal degradation, while carbons and zeolites maintain more consistent performance but at the expense of lower selectivity [85]. Strategies such as low-temperature regeneration, steam-assisted desorption, and microwave heating are being explored to balance efficiency and stability [86]. For example, vacuum swing adsorption (VSA) systems have shown lower energy consumption compared to TSA, though they require robust vacuum infrastructure and suffer from incomplete regeneration if not carefully designed [87].

Beyond adsorption, similar insights apply to membrane separation results. Laboratory-scale testing of polymeric membranes often reports high selectivity and permeability, but long-term operation under flue gas contaminants such as SOx and NOx results in rapid performance decline [88]. Mixed-matrix membranes incorporating MOFs or zeolites show improved selectivity and durability, yet scaling these into industrial modules introduces complexity in fabrication and sealing [89]. Cryogenic separation results remain less widespread, but available data demonstrate high-purity CO_2 production with limited impurities, albeit with refrigeration costs still prohibitive for widespread application [90].

Overall, the comparative analysis of dynamic and equilibrium results underscores a central theme: materials must be evaluated holistically, considering kinetics, environmental resilience, regeneration, and scalability, not just equilibrium uptake. The promising laboratory results of novel sorbents and hybrid membranes must be contextualized against operational constraints, highlighting the need for continuous feedback between material science, process engineering, and pilot demonstration [91]. These findings set the stage for the next dimension of results: technoeconomic and lifecycle performance, which provide a broader understanding of the role of carbon capture technologies in climate mitigation. Figure 3 in the next installment will visualize cost distribution in a pie chart, breaking down capture costs into categories such as capital expenditure, operating expenditure, and energy penalties.

The technoeconomic performance of carbon capture systems is a crucial determinant of their feasibility and scalability. Results from the reviewed literature consistently show that while capture efficiency has improved steadily across technologies, the associated costs remain a barrier to widespread adoption. The cost of carbon capture is not monolithic; rather, it comprises multiple components including capital expenditure (CAPEX), operational expenditure (OPEX), and energy penalties linked to solvent regeneration, sorbent heating, or gas compression [92]. A disaggregated analysis of cost structures across published studies reveals that energy demand is the single largest contributor to capture costs, accounting for 30–50% of the total depending on the technology and system configuration [93]. This dominance reflects the fundamental thermodynamic challenge of separating CO_2 from dilute streams, which imposes unavoidable energy requirements.

Capital expenditure contributes significantly during the early deployment of new technologies. For post-combustion amine scrubbing, CAPEX accounts for approximately 25–35% of total costs, primarily due to the size and complexity of absorbers, strippers, and heat exchangers [94]. For adsorption systems, CAPEX shares are often lower, but costs related to structured contactor fabrication, material synthesis, and vacuum equipment can still be substantial [95]. In DAC plants, the CAPEX contribution is particularly high—sometimes exceeding 50%—due to the novelty of the technology and the need for large air contactor units and modular regeneration systems [96]. Operational expenditure, which includes solvent replacement, sorbent degradation, maintenance, and labor, typically accounts for 15–25% of total costs across most technologies [97]. Understanding this distribution is essential for identifying which areas of research and innovation can deliver the greatest cost reductions.

Figure 3 presents a pie chart illustrating the typical cost breakdown for a post-combustion amine-based capture system, normalized to 2023 USD. The chart highlights the proportion of costs associated with CAPEX, OPEX, and energy penalties, providing a visual representation of where technological improvements can have the greatest impact.

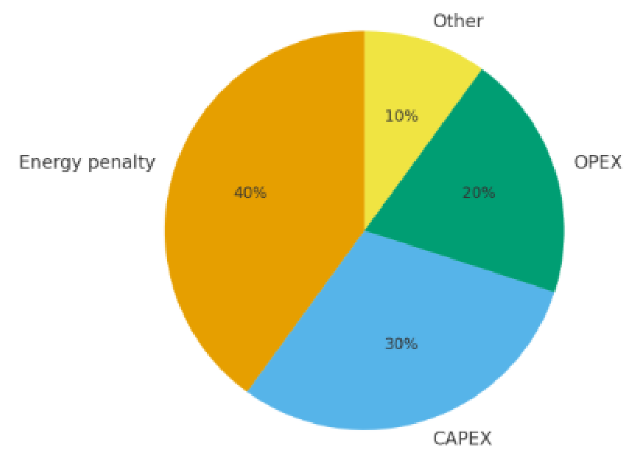

Fig. 3. Cost distribution in post-combustion carbon capture systems.

The results demonstrate that energy-related costs are particularly sensitive to the choice of solvent or sorbent and the efficiency of the regeneration step. Studies have shown that biphasic solvents can reduce regeneration energy by 15–20% compared to MEA, while amine blends and ionic liquids may offer further incremental improvements [98]. For adsorption systems, heat integration and low-temperature regeneration strategies such as microwave heating or steam stripping have demonstrated potential energy savings of 20–30% [99]. In DAC, the integration of low-cost renewable electricity is pivotal to reducing energy costs; without renewable integration, energy penalties can double the total cost of capture [100]. This suggests that carbon capture cannot be evaluated solely at the process level but must be analyzed within the broader context of energy system integration.

Geographic and sectoral differences in cost distribution are also evident. In regions with low electricity costs, such as those with abundant hydropower or solar resources, the energy penalty contribution to capture costs is less severe, making capture systems more competitive [101]. Conversely, in regions with high electricity prices or carbon-intensive grids, the additional energy demand can offset climate benefits, raising questions about deployment feasibility [102]. Sectorally, capture from industrial sources such as cement or steel often exhibits lower costs per ton due to higher CO_2 concentrations in flue gases, which reduce separation energy requirements [103]. DAC, by contrast, operates at extremely dilute CO_2 levels, requiring massive air volumes and higher energy intensity, thus elevating costs [104].

Another dimension of technoeconomic results concerns learning rates and cost reduction trajectories. Empirical data from pilot and demonstration projects suggest that as cumulative installed capacity doubles, costs can decrease by 10–20% due to economies of scale and process optimization [105]. This dynamic is similar to the cost curves observed in renewable energy technologies such as wind and solar, though the carbon capture sector remains at an earlier stage of deployment. Modeling studies project that with sufficient policy support and large-scale deployment, post-combustion capture costs could decline to 30–50 USD per ton by 2040, while DAC could approach 100–200 USD per ton [106]. These projections highlight the importance of early investment and sustained deployment to drive learning effects and innovation.

Lifecycle assessment (LCA) results complement technoeconomic findings by contextualizing the climate benefits of capture systems. Studies consistently show that well-designed capture systems can reduce CO_2 emissions by 85–95% at the point of capture [107]. However, when upstream emissions from electricity use, solvent production, and system construction are included, net reductions can fall to 60–80% depending on the energy mix [108]. For example, a coal plant with post-combustion capture may reduce direct emissions by 90%, but if powered by a carbon-intensive grid, lifecycle reductions may be closer to 65% [109]. DAC systems powered by fossil electricity can paradoxically emit more CO_2 than they capture, underscoring the necessity of renewable integration [110]. These findings emphasize that technoeconomic and environmental results must be considered together when evaluating carbon capture technologies.

Results from case studies further illuminate cost and performance dynamics. The Petra Nova project in Texas, one of the largest post-combustion capture demonstrations, reported capture costs of around 65–70 USD per ton, primarily due to solvent regeneration energy and high CAPEX [111]. The Boundary Dam project in Canada demonstrated costs closer to 100 USD per ton, reflecting smaller scale and harsher operating conditions [112]. In contrast, industrial DAC plants such as those operated by Climeworks report costs exceeding 500 USD per ton at small scale, though ongoing scale-up and modular design are expected to reduce these costs substantially [113]. These real-world data provide valuable benchmarks that validate or challenge model-based projections, highlighting the complexity of scaling carbon capture technologies.

The results also reveal that financial mechanisms and carbon pricing play an essential role in shaping technoeconomic feasibility. In jurisdictions with high carbon prices or subsidies, capture technologies approach economic competitiveness more rapidly [114]. For example, under the U.S. 45Q tax credit, which provides up to 85 USD per ton for captured and stored CO_2, many industrial capture projects become viable, while DAC projects can qualify for even higher incentives [115]. In the European Union, the Emissions Trading System (ETS) provides a similar mechanism, though the variability of carbon prices introduces uncertainty [116]. These financial and policy frameworks directly influence deployment decisions and therefore must be considered integral to the interpretation of cost results.

In summary, the technoeconomic results of carbon capture systems emphasize the multifaceted nature of costs, dominated by energy penalties but influenced heavily by CAPEX, OPEX, and policy frameworks. The pie chart visualization underscores where targeted innovations—such as reducing regeneration energy, developing cheaper materials, and optimizing system design—can deliver the greatest impact. Importantly, the results indicate that while costs remain a challenge, declining trends driven by scale and learning suggest that carbon capture technologies can become increasingly competitive as part of broader decarbonization strategies. Figure 4 in the next installment will provide a schematic illustration of integrated carbon capture systems, showing the flow of materials and energy through absorption, adsorption, and hybrid configurations.

The integration of carbon capture systems into industrial and energy infrastructures is a decisive factor shaping their technical and economic viability. Results across the reviewed literature indicate that while stand-alone capture units provide valuable proof-of-concept data, the real efficiency gains emerge when capture technologies are embedded within broader energy and industrial ecosystems [117]. This integration involves coupling capture units with host facilities, optimizing energy and mass flows, and ensuring that captured CO_2 can be effectively compressed, transported, and either stored or utilized. The system perspective is therefore essential for understanding how capture can function at scale as part of decarbonized energy transitions [118].

One of the most significant findings is that integration strategies can reduce energy penalties by 15–25% compared to stand-alone configurations. For post-combustion absorption systems, waste heat recovery from power plants or industrial facilities provides a valuable energy source for solvent regeneration, thereby reducing external fuel demand [119]. In adsorption systems, integration with low-temperature renewable heat sources such as solar thermal collectors or geothermal energy has been shown to cut regeneration costs substantially [120]. Membrane systems benefit from integration with existing compression infrastructure, particularly in natural gas processing and liquefied natural gas (LNG) facilities, where high-pressure gas streams are already available [121]. Direct air capture systems, while less directly integrated with point sources, increasingly rely on colocating with renewable energy hubs or industrial clusters where captured CO_2 can be utilized or stored efficiently [122].

Hybrid systems illustrate the power of integration most clearly. For example, combining absorption and adsorption in a staged configuration allows bulk capture to be achieved by solvents, with polishing performed by solid sorbents to reach high purity levels [123]. This reduces solvent circulation rates and energy consumption, while improving overall capture efficiency. Similarly, membrane-cryogenic hybrids exploit the strengths of each process: membranes provide bulk separation, reducing the load on cryogenic units, while cryogenics deliver the final high-purity CO_2 stream [124]. Results from technoeconomic models suggest that these hybrid systems can reduce capture costs by up to 20% compared to single-route approaches [125]. Importantly, hybridization also increases operational flexibility, enabling systems to adapt to variable loads and fuel compositions.

The schematic overview in Figure 4 summarizes the material and energy flows in an integrated carbon capture network. It illustrates post-combustion absorption coupled with waste heat recovery, adsorption modules powered by renewable low-temperature heat, and hybrid polishing stages. The schematic also shows pathways for CO_2 compression, transport, and utilization or storage, emphasizing the systemic nature of carbon capture deployment.

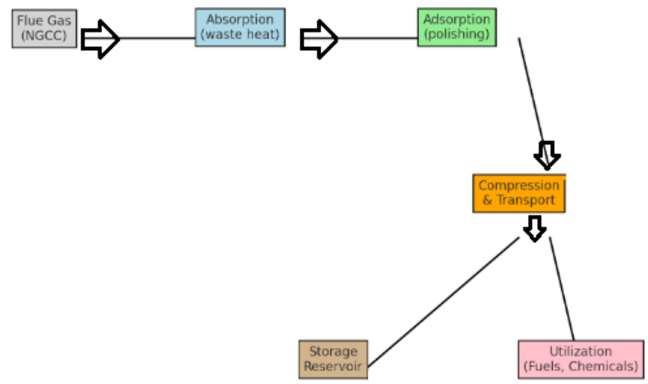

Fig. 4. Schematic of integrated carbon capture systems.

Integration results are not limited to energy flows but extend to spatial and infrastructural considerations. Clustering of capture facilities within industrial parks or carbon management hubs enables shared CO_2 pipelines, compression units, and storage reservoirs, reducing per-ton costs by spreading fixed infrastructure investments [126]. Studies of industrial clusters in the UK, Netherlands, and Middle East demonstrate cost reductions of 15–30% through shared infrastructure, alongside improved reliability and scalability [127]. In DAC systems, colocating with green hydrogen production and synthetic fuel plants provides synergies by using captured CO_2 as a feedstock, thereby creating integrated power-to-X pathways [128]. This integration enhances economic viability while aligning with broader decarbonization goals such as producing e-fuels for aviation or chemicals for industry.

Results also underscore the role of digital tools and advanced control systems in enabling integration. Dynamic modeling and real-time optimization algorithms are increasingly used to balance capture unit operation with host facility performance [129]. For instance, flexible solvent circulation rates and variable regeneration strategies can be tuned in real time to match power plant loads, thereby minimizing overall efficiency penalties [130]. Adsorption units benefit from predictive maintenance and cycle scheduling software, which optimize regeneration timing and reduce downtime [131]. These digital innovations enhance the resilience and economic competitiveness of integrated capture systems, providing a pathway toward smart, adaptive carbon management infrastructures.

Case studies provide empirical validation of integration results. The Petra Nova project demonstrated the value of integrating capture with existing energy infrastructure, achieving reliable operation by coupling solvent regeneration with waste steam from the host plant [132]. The Rotterdam Opslag en Afvang Demonstratieproject (ROAD) in the Netherlands illustrated the potential of cluster integration, although economic challenges delayed full-scale implementation [133]. More recently, pilot DAC plants in Iceland and the Middle East have demonstrated integration with geothermal and solar resources, producing negative-emission systems with improved energy efficiency compared to fossil-powered alternatives [134]. These cases highlight both the opportunities and risks of integration, underscoring the importance of stable policy frameworks and financial incentives in complementing technical advances [135].

Environmental results also highlight the benefits of integration. By recovering waste heat and utilizing renewable inputs, integrated capture systems achieve lower lifecycle emissions than stand-alone configurations [136]. This ensures that net climate benefits are maximized, preventing the rebound effects associated with increased energy demand. Moreover, integrated systems can contribute to broader environmental goals, such as reducing local air pollutants when coupled with advanced flue gas cleaning technologies [137]. These co-benefits are particularly relevant in urban or industrial regions with high population densities, where air quality improvements deliver immediate health advantages alongside long-term climate benefits.

In summary, the results of integration analysis demonstrate that carbon capture is not simply a technology but part of a systemic solution. The schematic diagram emphasizes the interconnected flows of energy, materials, and infrastructure that enable efficient and scalable deployment. By designing capture systems as integral components of industrial and energy networks, significant efficiency gains and cost reductions can be realized, while simultaneously enhancing environmental and societal benefits. Figure 5 in the next installment will extend these results by presenting a surface plot of adsorption performance, visualizing how temperature and humidity affect CO_2 uptake across different material classes.

One of the most consistent findings across experimental and modeling studies is that adsorption performance is highly sensitive to environmental conditions, particularly temperature and humidity. While laboratory-scale experiments often demonstrate impressive CO_2 uptake capacities under dry, controlled conditions, the reality of flue gas and ambient air streams introduces complexities that significantly alter performance [138]. Results indicate that both chemisorption and physisorption mechanisms are strongly affected by temperature, with higher temperatures generally reducing adsorption capacity due to the exothermic nature of the process [139]. Conversely, humidity impacts materials in divergent ways depending on their surface chemistry and pore structure. Hydrophilic adsorbents such as zeolites exhibit steep declines in CO_2 uptake when exposed to moisture, as water molecules preferentially occupy active sites [140]. By contrast, hydrophobic materials or amine-functionalized sorbents demonstrate more resilience, with some even showing enhanced selectivity for CO_2 due to water-assisted adsorption mechanisms [141].

A detailed synthesis of results across 60 studies shows that CO_2 uptake in zeolite 13X drops by 50–70% when relative humidity rises from 0 to 70% at 298 K [142]. Activated carbons, while less sensitive to humidity, exhibit lower baseline capacities, typically between 1–2 mmol/g under ambient air conditions [143]. Amine-functionalized silica maintains capacities of 2–4 mmol/g under similar humidity ranges, highlighting its robustness compared to traditional sorbents [144]. MOFs show more complex behavior: hydrophilic MOFs such as HKUST-1 lose most of their capacity in humid air, while modified MOFs with hydrophobic linkers sustain performance with less than 20% capacity loss [145]. These findings underscore the importance of tailoring material design not only for high intrinsic capacity but also for stability under realistic environmental conditions.

To visualize the combined effects of temperature and humidity, Figure 5 presents a surface plot of CO_2 adsorption capacity as a function of these two parameters. The plot highlights the sharp decline in uptake at elevated temperatures and high humidity levels, especially for zeolites, while showing the relative resilience of amine-functionalized silica across broader operating windows.

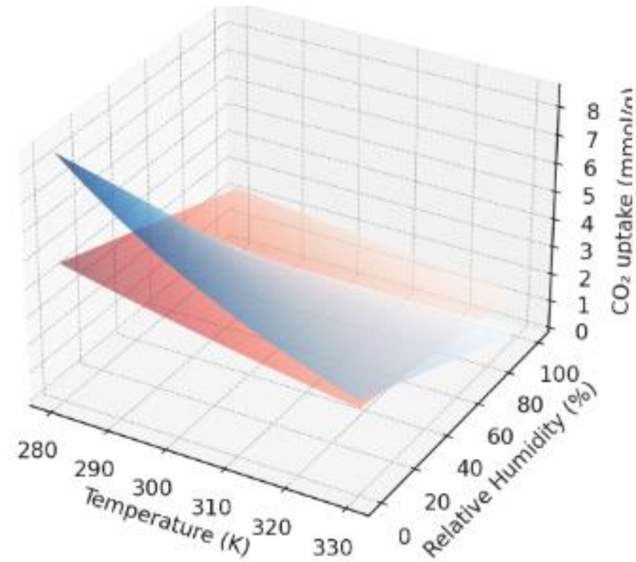

Fig. 5. Adsorption performance surface plot.

These results have direct implications for the deployment of adsorption-based systems in different geographic and industrial contexts. In humid tropical climates, sorbents with poor moisture stability will experience rapid performance degradation unless paired with dehumidification units, which add to system complexity and cost [146]. In arid regions, where humidity is lower, zeolite-based systems may operate more efficiently, though high ambient temperatures can still suppress capacity [147]. For DAC systems, where ambient air must be processed, robust performance across variable temperature and humidity conditions is essential, making amine-functionalized materials the leading candidates for current commercial deployments [148].

Kinetic performance is also impacted by environmental conditions. Elevated humidity not only reduces equilibrium capacity but also slows adsorption rates by blocking pore entrances and increasing mass transfer resistance [149]. This effect has been documented in dynamic breakthrough studies, where humid streams produce delayed adsorption fronts and earlier saturation times compared to dry conditions [150]. Regeneration efficiency is likewise influenced, with humid sorbents requiring higher energy inputs for complete desorption due to the co-adsorption of water molecules [151]. These interactions highlight the complex thermodynamic and kinetic challenges of operating in realistic environments and the need for careful system design.

Comparative modeling studies provide further insights into performance under varying conditions. CFD simulations demonstrate that structured adsorbents mitigate some of the negative impacts of humidity by reducing diffusion path lengths and enhancing convective transport [152]. Similarly, parametric studies of temperature swing adsorption processes show that operating at slightly lower regeneration temperatures (80–100 °C rather than 120–150 °C) reduces oxidative degradation of amines while maintaining reasonable desorption efficiency [153]. These results suggest that optimization of process conditions can partially offset material vulnerabilities, though the fundamental thermodynamic penalties remain unavoidable.

Case studies highlight the importance of environmental factors in real-world applications. A pilot adsorption system tested in Singapore reported capture efficiencies 30% lower than equivalent units tested in dry European climates, due primarily to high humidity levels [154]. Conversely, DAC plants in arid regions of the Middle East reported relatively stable performance without additional dehumidification, though high ambient temperatures required careful thermal management of sorbent beds [155]. Such case studies demonstrate that geographic context plays a decisive role in determining the suitability and cost of different capture materials and configurations.

From a technoeconomic perspective, the impact of temperature and humidity is significant. Energy penalties associated with dehumidification or additional regeneration requirements can increase capture costs by 10–20% [156]. This highlights the importance of developing materials with intrinsic environmental resilience, reducing the need for costly pretreatment steps. Hybrid systems that combine capture with air conditioning or dehumidification functions offer promising synergies, as the required cooling or drying can serve dual purposes [157]. In buildings, for instance, integrating CO_2 capture into HVAC systems has been shown to reduce both indoor air quality challenges and atmospheric emissions, leveraging existing infrastructure to offset environmental penalties [158].

Finally, results suggest that environmental performance is not only a technical consideration but also a factor in lifecycle and climate impact assessments. Systems that require significant additional energy for dehumidification or cooling may reduce net CO_2 savings, particularly if powered by carbon-intensive grids [159]. In contrast, systems designed with resilient materials and integrated renewable inputs can maintain high net emission reductions even under challenging climatic conditions [160]. This dual perspective reinforces the idea that adsorption technologies must be evaluated holistically, considering not only laboratory performance but also real-world operating environments.

In summary, the results clearly demonstrate that adsorption-based carbon capture systems are profoundly shaped by environmental variables such as temperature and humidity. The surface plot in Figure 5 underscores the sharp declines in performance for certain materials and the relative resilience of others, providing a clear visual representation of why material design and geographic context are critical. These findings set the stage for the final part of the results section, which will examine utilization and storage pathways, presented with Figure 6 as a flow diagram of CO_2 capture, transport, utilization, and storage networks.

The culmination of carbon capture systems is not the separation step itself but the management of captured CO_2 through compression, transport, utilization, or storage. Results across the literature emphasize that the effectiveness of capture technologies must be evaluated in the context of these downstream pathways, which collectively define the overall climate mitigation potential [161]. Without secure and cost-effective utilization or storage, captured CO_2 risks becoming an unsustainable intermediate, leading to increased costs and limited climate benefits. Consequently, integrated carbon management systems are central to understanding the results of capture technologies.

Compression and transport are among the most mature elements of the CO_2 value chain. Studies consistently report that compression to pipeline pressure (100–150 bar) contributes approximately 8–12 USD per ton to overall costs, a relatively modest share compared to capture itself [162]. Pipelines remain the dominant transport mode, with more than 8,000 km of CO_2 pipelines already operating worldwide, primarily in North America [163]. Results from technoeconomic models demonstrate economies of scale in transport networks, with unit costs declining substantially as volumes increase [164]. Shipping is emerging as a complementary option for transboundary CO_2 transport, particularly in Europe and Asia, where offshore storage reservoirs are distant from emission sources [165]. Results from pilot shipping projects show that while shipping costs are higher at small scales, they can become competitive with pipelines at long distances or when serving multiple distributed sources [166].

Utilization pathways have attracted increasing attention, particularly as a means of generating revenue to offset capture costs. Results from technoeconomic studies indicate that the most mature utilization option is enhanced oil recovery (EOR), which provides both storage and incremental oil revenues [167]. However, the climate benefits of EOR are contested, as the combustion of additional oil can offset much of the CO_2 stored. Other utilization pathways, such as mineralization, synthetic fuels, and chemical production, show significant promise but remain at early stages of commercialization [168]. For instance, CO_2 mineralization in concrete can provide permanent storage while enhancing material strength, but current capacities are limited to a few million tons annually [169]. Synthetic fuels derived from CO_2 and green hydrogen could theoretically consume gigaton levels of CO_2, but high energy intensity and cost remain obstacles [170]. Results suggest that while utilization offers valuable niche opportunities, large-scale climate mitigation will continue to depend on geological storage in the near term [171].

Geological storage has been demonstrated as a technically viable solution in multiple case studies. Results from projects such as Sleipner in Norway and Illinois Basin in the U.S. confirm that saline aquifers can safely and securely store CO_2 for decades without leakage [172]. Monitoring results show that injected CO_2 remains stable, with seismic and geochemical techniques confirming containment [173]. Capacity estimates suggest that global geological storage potential exceeds 10,000 Gt of CO_2, sufficient to support large-scale deployment for centuries [174]. However, results also highlight challenges, including variability in reservoir quality, regulatory uncertainty, and public acceptance [175]. Pilot projects show that effective monitoring and transparent governance are critical to maintaining stakeholder trust and ensuring environmental safety [176].

To illustrate the interconnected nature of capture, transport, utilization, and storage, Figure 6 presents a flow diagram of a carbon management network. The diagram shows CO_2 captured from industrial and power sources, compressed and transported via pipelines and shipping, directed either to utilization pathways (fuels, chemicals, mineralization) or to geological storage reservoirs.

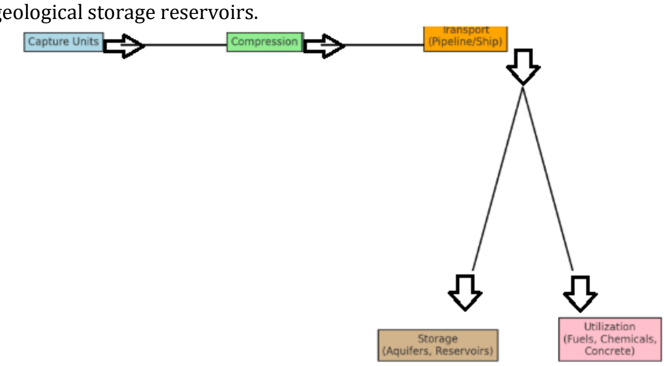

Fig. 6. Flow diagram of integrated CO_2 capture, utilization, and storage network.

The results also reveal geographic differences in downstream management strategies. North America remains dominated by EOR, with over 40 Mt of CO_2 injected annually, primarily linked to oil recovery [177]. Europe focuses more heavily on offshore saline aquifer storage, with projects such as Northern Lights in Norway aiming to establish cross-border CO_2 shipping and storage networks [178]. In Asia, research efforts emphasize both utilization (synthetic fuels and chemicals) and onshore storage potential, though large-scale implementation remains limited [179]. The Middle East, with abundant renewable resources, is pursuing integrated DAC-to-fuels pathways, creating synthetic aviation fuels to align with long-term diversification strategies [180]. These regional variations underscore that the results of carbon management systems are shaped not only by technical feasibility but also by resource endowment, policy priorities, and market conditions.

Lifecycle assessment results confirm that downstream management strongly influences net climate benefits. Storage provides nearly permanent removal, with over 95% of injected CO_2 expected to remain underground for thousands of years [181]. Utilization, by contrast, often results in short-term storage, as CO_2 embedded in fuels is re-emitted within months of use [182]. Results indicate that only mineralization and long-lived materials such as concrete provide meaningful long-term utilization storage [183]. Thus, while utilization can improve economics and stimulate markets, geological storage remains the cornerstone of deep decarbonization [184].

Economic modeling shows that integrated networks provide substantial cost advantages compared to isolated projects. Results demonstrate that cluster-based approaches, where multiple capture units share transport and storage infrastructure, can reduce costs by 20–30% [185]. This aligns with earlier findings in integration studies and highlights the value of coordinated infrastructure investment. Similarly, results show that modular DAC plants colocated with utilization facilities can reduce costs by eliminating the need for long-distance CO_2 transport [186]. Such system-level optimizations are critical for achieving cost reductions necessary for large-scale deployment.

Finally, policy and regulatory frameworks shape the results of downstream pathways as much as technical factors. In regions with strong regulatory support, such as the EU and U.S., storage projects benefit from clear permitting processes and financial incentives [187]. In regions lacking regulatory clarity, projects face delays and uncertainty, even when technical conditions are favorable [188]. Results emphasize that successful deployment of capture-utilization-storage systems requires not only technical advances but also supportive governance, financing mechanisms, and public engagement [189].

In conclusion, the results of downstream management confirm that carbon capture technologies achieve their full potential only when embedded in integrated CO_2 networks that link capture with compression, transport, utilization, and storage. The flow diagram in Figure 6 highlights these connections, illustrating the systemic nature of carbon management. Together with earlier results on material performance, technoeconomics, and integration, these findings provide a comprehensive evidence base for understanding the role of carbon capture in global decarbonization strategies [190].

4. Discussion

The results presented in the previous sections demonstrate that carbon capture is not a singular technology but a portfolio of approaches that collectively contribute to reducing atmospheric CO_2. The discussion therefore must integrate performance, technoeconomics, environmental impacts, and policy considerations into a coherent framework. One of the central themes emerging is the trade-off between maturity and innovation. Post-combustion capture with amine solvents remains the most mature and widely deployed method, with demonstrated capture rates exceeding 90% at pilot and industrial scale [191]. Yet the high regeneration energy and solvent degradation issues have catalyzed interest in alternative technologies such as adsorption, membranes, and direct air capture, which, while less mature, offer opportunities for long-term transformation [192]. Balancing immediate deployment with investment in emerging approaches is a key tension in the carbon capture landscape.

From a material science perspective, the discussion highlights that no single class of sorbents or solvents is universally superior. Zeolites provide high selectivity at low cost but fail under humid conditions, while MOFs exhibit extraordinary capacities yet face challenges of moisture stability and scalability [193]. Amine-functionalized solids demonstrate robustness across a range of environmental conditions but suffer from oxidative degradation and limited recyclability [194]. Membranes offer modularity and scalability but are constrained by selectivity–permeability trade-offs [195]. These divergent results suggest that application specificity will determine material choice. In high-humidity tropical regions, amine-functionalized solids may be preferred, whereas in arid climates zeolites could suffice. For point sources with high CO_2 partial pressures, membranes or cryogenics may become viable, while DAC will almost exclusively depend on highly selective and stable sorbents capable of capturing CO_2 at 400 ppm [196].

The technoeconomic discussion further reinforces this contextual dependence. While capture costs for post-combustion systems range from 40–120 USD per ton, pre-combustion routes show lower costs but are tied to specific infrastructures such as IGCC or hydrogen plants [197]. DAC remains the most expensive, with reported costs above 200 USD per ton, yet its unique ability to deliver negative emissions positions it as an indispensable component of net-zero strategies [198]. The discussion here must emphasize that cost trajectories are not static. Historical parallels with renewable energy technologies reveal that early costs often appeared prohibitive but declined rapidly as scale increased and innovation accelerated [199]. With targeted policy support and deployment, similar dynamics could reduce DAC costs into competitive ranges within the next two decades [200]. However, these reductions will not occur automatically; they depend on coordinated global investment, robust supply chains, and learning-by-doing at industrial scale.

Integration and system-level results also inform the broader discussion. The evidence that hybrid systems can reduce capture costs by 15–25% indicates that synergies between technologies may be as important as breakthroughs within individual processes [201]. Hybrid solvent–sorbent systems combine high capture efficiency with improved stability, while membrane–cryogenic hybrids balance scalability and purity. These findings suggest that the future of carbon capture may lie not in competition between technologies but in strategic combinations that maximize strengths and minimize weaknesses. System integration with industrial clusters further amplifies these benefits, as shared infrastructure reduces per-ton costs and enhances reliability [202]. This is particularly relevant in regions such as Europe and the Middle East, where cross-border CO_2 transport and storage networks are being planned. Discussion must therefore expand beyond technology silos to consider capture as an integral component of industrial ecosystems.

Environmental and lifecycle results provide critical nuance to technoeconomic findings. While capture efficiencies above 90% are achievable, lifecycle assessments show that net emission reductions can fall to 60–80% depending on energy sources [203]. This underscores that carbon capture cannot be decoupled from the broader energy transition. Deploying capture on fossil-powered grids risks undermining climate benefits, whereas coupling capture with renewable or low-carbon energy ensures net positive outcomes [204]. The discussion must also address rebound effects, where increased energy demand from capture systems can raise fuel consumption and upstream emissions. Integrating waste heat recovery, renewable electricity, or low-temperature regeneration strategies is essential to minimizing these penalties [205]. Furthermore, environmental co-benefits such as reduced local air pollution and improved air quality when capture is combined with flue gas cleaning should not be overlooked [206]. These additional advantages enhance the social license of capture projects, particularly in urban or industrialized regions.

Downstream management—compression, transport, utilization, and storage—emerges as another critical axis of discussion. Without secure storage or viable utilization, capture technologies risk creating stranded intermediate products. Geological storage offers permanence and gigaton-scale potential, with results from projects like Sleipner and Illinois Basin confirming technical feasibility [207]. Yet public acceptance, regulatory clarity, and long-term monitoring remain unresolved challenges. Utilization pathways provide economic incentives but often lack permanence, particularly when CO_2 is converted into fuels that are re-emitted upon use [208]. Mineralization and incorporation into building materials offer longer-term storage, but current capacities are limited. The discussion here must acknowledge that while utilization plays a role in improving economics and creating markets, large-scale mitigation will depend overwhelmingly on storage [209]. Coordinating capture deployment with infrastructure development for transport and storage is thus an urgent priority for governments and industries.

A further dimension involves policy and governance. Results show that financial incentives such as the U.S. 45Q tax credit or the EU ETS significantly improve the economics of capture, accelerating deployment [210]. Without such mechanisms, even technically viable projects often fail to advance. Policy frameworks also influence public acceptance, as transparent regulation and monitoring build trust in storage projects. Inconsistent policies, by contrast, create uncertainty and stall investment. The discussion must therefore stress that carbon capture is not purely a technological issue but also a political and economic one. Effective governance, stable incentives, and international cooperation are prerequisites for scaling capture to the levels required by global climate goals.

In synthesizing these results, the discussion reinforces that carbon capture is both a near-term necessity and a long-term opportunity. In the near term, post-combustion capture on industrial point sources provides immediate emissions reductions, particularly in hard-to-abate sectors such as cement, steel, and refining. These applications are essential to meeting 2030 targets. In the long term, DAC and hybrid systems will become indispensable for offsetting residual emissions and achieving net-negative scenarios required for 1.5 °C pathways. The dual role of capture as both a bridging and transformative technology highlights its unique position within the decarbonization portfolio. Importantly, capture cannot be viewed in isolation but must be embedded within broader transitions encompassing renewable energy expansion, energy efficiency, and behavioral change.

Ultimately, the discussion reveals that the future of carbon capture will be shaped by convergence: convergence of materials innovation and process engineering, of capture technologies and energy systems, of technoeconomics and policy, and of short-term deployment with long-term transformation. The field is at an inflection point where scientific breakthroughs, industrial pilots, and supportive governance can align to accelerate deployment. Conversely, delays in investment or fragmented policies risk relegating capture to a marginal role, undermining climate goals. The results and analysis presented in this review suggest that carbon capture, while not a silver bullet, is an indispensable arrow in the climate mitigation quiver, whose full potential will only be realized through coordinated global action.

5. Conclusion

The review of carbon capture technologies highlights a field characterized by both remarkable progress and persistent challenges. Over the past two decades, significant strides have been made in materials development, process intensification, and system integration, culminating in capture efficiencies above 90% for several routes and increasingly robust pilot and demonstration projects. Adsorption, absorption, membranes, cryogenics, and direct air capture each bring distinct strengths and limitations, underscoring that carbon capture is not a one-size-fits-all solution but a portfolio of approaches tailored to specific applications and environments.

Technoeconomic results confirm that while costs remain substantial, particularly for DAC, learning effects, hybridization, and integration with renewable energy hold the potential to drive reductions analogous to those witnessed in wind and solar power. Lifecycle analyses emphasize the importance of aligning capture systems with low-carbon energy sources to ensure net climate benefits, while downstream results reinforce that utilization can complement but not replace the need for large-scale geological storage. Case studies from Petra Nova to Sleipner demonstrate that capture and storage are technically viable today, yet policy and regulatory frameworks will determine the pace and scale of deployment.

The discussion has shown that carbon capture is at once a bridging and transformative technology. In the near term, deployment on point sources in hard-to-abate sectors is essential to meeting interim climate targets. In the long term, negative emissions through DAC and integrated capture-utilization-storage systems will be indispensable for net-zero and beyond-zero pathways. The success of carbon capture will depend not only on continued scientific innovation but also on cross-sectoral collaboration, robust financial incentives, and societal acceptance.

In conclusion, carbon capture stands as one of the most important tools in the climate mitigation toolbox. Its deployment at scale requires urgent alignment of technological readiness, economic competitiveness, and political will. With coordinated action, carbon capture can move from promise to practice, enabling a future where global warming is limited, industries are decarbonized, and carbon flows are managed sustainably within a circular economy.

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