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Carbon Capture, Utilization, and Storage: Solvents, Sorbents, Membranes, and Process Intensification

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Abstract

This review aims to synthesize recent advances in carbon capture, utilization, and storage (CCUS) technologies, focusing on solvents, sorbents, membranes, and process intensification strategies to identify trends, challenges, and future directions. A qualitative literature review was conducted on 15 high-impact peer-reviewed articles published between 2010 and 2025. The studies were selected based on relevance to solvent-based, sorbent-based, and membrane-based CO_2 capture, as well as process intensification approaches and utilization or storage pathways. Data were collected exclusively from the literature and analyzed using thematic qualitative methods in NVivo 14. Open, axial, and selective coding were applied until theoretical saturation was achieved, extracting main themes, subthemes, and concepts related to materials performance, process design, and carbon utilization and storage. Three main themes emerged. First, advanced carbon capture materials—including novel solvents, solid sorbents, membranes, and hybrid systems—demonstrate improved CO_2 selectivity, stability, and regeneration performance, though energy consumption and durability remain critical limitations. Second, process design and intensification strategies, such as rotating packed beds, microchannel reactors, and integrated absorption-membrane modules, enhance mass and heat transfer, reduce equipment size, and improve energy efficiency, particularly when coupled with robust modeling and simulation frameworks. Third, carbon utilization and storage pathways, encompassing mineralization, chemical conversion, and geological sequestration, highlight the potential to close the carbon loop while minimizing lifecycle emissions. Policy, regulatory frameworks, and social acceptance influence deployment but remain underrepresented in technical studies. The integration of advanced materials with process intensification and utilization/storage strategies is essential for scalable, efficient, and economically viable CCUS systems. Future research should focus on pilot-scale validation, multi-objective optimization, and lifecycle assessment to bridge laboratory innovations with industrial application. Comprehensive system-level approaches combining technical, economic, and societal considerations will be crucial to accelerate the deployment of CCUS technologies in achieving global net-zero targets.

Keywords: Carbon capture, Carbon utilization, Carbon storage, Solvents, Sorbents, Membranes, Process intensification, CO_2 mitigation

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1. Introduction

The accelerating pace of global industrialization and energy demand has intensified concerns regarding anthropogenic CO_2 emissions and their impact on Earth's climate. As the world seeks pathways to limit warming and stabilize atmospheric concentrations, carbon capture, utilization, and storage (CCUS) has emerged as a pivotal suite of technologies capable of bridging the gap between ambitious decarbonization goals and existing carbon-intensive infrastructures. While renewable energy deployment and electrification are indispensable parts of the decarbonization portfolio, they are unlikely in the near and medium term to eliminate all point-source CO_2 emissions. In this context, CCUS offers a complementary and sometimes essential option to mitigate emissions from power plants, industrial processes, and sectors that are difficult to decarbonize directly.

The concept of CCUS entails capturing CO_2 from concentrated sources (or even from ambient air), converting or utilizing it in value-added products, and/or storing it in geologic formations for the long term. In the capture phase, a major technical challenge lies in developing materials and processes that can separate CO_2 from multicomponent gas streams with high selectivity, low energy penalty, fast kinetics, chemical stability, and toleration of impurities such as SO_x, NO_x, water vapor, and trace contaminants (U.S. Department of Energy, 2015; Osman et al., 2021). Among capture strategies, solvent absorption remains the most mature and widely deployed approach, owing to its high capture efficiency and scalability in industrial settings. Nevertheless, conventional amine solvents such as monoethanolamine (MEA) suffer significant drawbacks: high regeneration energy, oxidative and thermal degradation, corrosion, and degradation by-products (Osman et al., 2021). To overcome these limitations, research has turned toward advanced solvents (e.g., blended amines, sterically hindered amines, ionic liquids, and phase-change solvents) that promise enhanced stability, reduced regeneration energy, and improved cyclic performance (Bhattacharyya, 2017; Review of Carbon Capture Absorbents, 2022).

In parallel, solid sorbent materials have gained momentum because of their potentially lower energy requirements and modular deployment capability. Sorbents such as zeolites, activated carbons, silica, functionalized polymers, and particularly metal–organic frameworks (MOFs) or covalent organic frameworks (COFs) have exhibited high surface areas, tunable pore environments, and modifiable chemical functionalities optimized for CO_2 capture under various thermodynamic conditions (Sumida et al., 2012; Bui et al., 2018). Yet, challenges remain: water sensitivity, limited stability under flue gas contaminants, slow adsorption/desorption kinetics, and cyclic durability under real-world conditions (Wang, Luo, Zhong, & Borgna, 2020). Meanwhile, membrane-based separations are increasingly studied as low-energy alternatives for CO_2 capture. Membranes—whether polymeric, facilitated-transport, or mixed-matrix—offer continuous operation, lower footprint, and lower operational complexity, although trade-offs between permeability and selectivity, membrane aging, fouling, and stability under variable pressure and temperature remain critical obstacles (Sanders et al., 2013; Zhang, Li, & Zhao, 2023).

As the chemical and physical boundaries of individual capture material systems are pushed, a promising direction lies in hybrid or multifunctional materials and processes—where absorption, adsorption, and membrane separation may be combined or integrated to exploit synergistic effects and reduce systemic energy consumption. The co-design of materials and process architectures is increasingly recognized as vital to bridging lab-scale breakthroughs and industrially viable systems. For example, dual-functional sorbent–membrane composites or absorption–adsorption hybrid systems can enhance CO_2 flux, mitigate limitations of single modes, and better adapt to real flue gas conditions.

Yet material innovation alone is not sufficient for achieving commercially viable and large-scale CCUS deployment. Process engineering, especially process intensification, is crucial to reduce energy penalties, footprint, capital and operational costs, and to improve mass and heat transfer performance. Intensified unit operations—such as rotating packed beds, microchannel reactors, membrane contactors, ultrasound- or microwave-assisted desorption, and integrated absorption–conversion modules—seek to compress or eliminate stages in conventional designs, thereby improving throughput, lowering parasitic energy consumption, and reducing the size of equipment (Adamu, Russo-Abegão, & Boodhoo, 2020; Adamu et al., 2020). For instance, rotating packed beds (RPBs) can drastically enhance mass transfer coefficients by forcing fluids through high shear zones, which in turn can reduce the required equipment volume and regeneration energy (Jung, Park, & Lee, 2024). Intensification in desorption processes—such as combining microwave heating or ultrasound with novel solvent systems—has also been explored to reduce regeneration energy and accelerate CO_2 release (Adamu et al., 2020; Process Intensification for CO_2 Desorption, 2021).

Beyond capture and intensification, the “utilization” leg of CCUS is increasingly important for closing the carbon loop and improving overall economic viability. CO_2 can be converted into chemicals, fuels, polymers, and building materials via catalytic, electrochemical, biochemical, or mineralization pathways. These routes, though varied in maturity, contribute to a circular carbon economy by turning a waste gas into value streams (Artz et al., 2018; Liu, Lu, & Wang, 2023). However, utilization routes must be judged not only on conversion efficiency but also on life-cycle CO_2 balance, energy inputs, and scalability. In parallel, **geological storage** remains the most mature and reliable option for large-scale sequestration, particularly via deep saline aquifers or depleted hydrocarbon reservoirs, and understanding reservoir integrity, leakage potential, caprock stability, and long-term monitoring is essential (Alcalde et al., 2018; Benson & Cole, 2008). Life-cycle assessment (LCA), techno-economic analysis (TEA), and environmental impact assessments are indispensable tools to evaluate the net efficacy of integrated CCUS systems and to guide sustainable deployment (Koornneef, van Keulen, Faaij, & Turkenburg, 2012; Cuéllar-Franca & Azapagic, 2015).

Despite the progress, CCUS still faces formidable challenges spanning technical, economic, and societal dimensions. The energy penalty associated with CO_2 capture remains significant, typically reducing net plant efficiency by 20–30 % for conventional systems (Osman et al., 2021). Scaling laboratory concepts to commercial scale invariably reveals issues related to mass/heat transfer, durability, impurity tolerance, stability, fouling, and control. Economic feasibility depends heavily on capital cost, operating expenditure, carbon pricing, subsidy frameworks, and regulatory incentives. Moreover, issues of public perception, regulatory uncertainty, liability for stored carbon, and policies about long-term storage safety and environmental justice further complicate deployment (Liu, Lu, & Wang, 2023). To overcome these hurdles, holistic system-level integration—from materials to process to economics to governance—is critically needed.

Given the multiplicity of materials and process strategies, there remains a pressing need to synthesize the evolving literature across solvents, sorbents, membranes, and intensification methods into a coherent framework. Many reviews treat these technologies individually (e.g., Bhattacharyya, 2017; Adamu et al., 2020), but fewer have systematically integrated cross-cutting insights into hybrid strategies, process–material co-design, and pathway trade-offs. This review aims to fill that gap by conducting a qualitative literature synthesis across multiple CCUS domains, focusing on how solvents, sorbents, and membranes can be advanced and integrated under process intensification paradigms to realize practical, scalable, and efficient carbon capture systems. We reviewed 15 representative, high-impact recent articles, applying qualitative coding and thematic analysis to extract the dominant trends, challenges, and prospective directions.

In doing so, this article hopes to provide: (1) an integrative perspective on the state-of-the-art in capture materials and intensification strategies; (2) a conceptual framework linking material advances with process-level design decisions; and (3) identification of research gaps and future directions in CCUS. Through this synthesis, we aim to inform both academic researchers and engineering practitioners of promising pathways that bridge lab-scale innovation and real-world deployment, ultimately contributing to accelerating the adoption of CCUS technologies in the global drive toward net-zero emissions.

2. Methods and Materials

This review adopted a qualitative research design based on systematic content analysis of the scientific literature on Carbon Capture, Utilization, and Storage (CCUS) technologies. The objective was to synthesize empirical and theoretical insights regarding solvents, sorbents, membranes, and process intensification strategies used in CO_2 capture and sequestration systems. Since this is a literature-based qualitative review, there were no human participants. Instead, peer-reviewed journal articles, technical reports, and authoritative review papers were treated as the "participants" of the study. These sources were selected to reflect multidisciplinary perspectives, including materials science, chemical engineering, process systems engineering, and energy policy.

The data collection was carried out through a systematic literature review of published works indexed in Scopus, Web of Science, and ScienceDirect between 2010 and 2025. The search strategy included keywords such as "carbon capture," "CO_2 utilization," "CO_2 storage," "amine solvents," "solid sorbents," "membrane separation," and "process intensification." A total of 15 relevant peer-reviewed articles were selected after applying inclusion and exclusion criteria.

The inclusion criteria required that articles explicitly address one or more of the following:

(1) experimental or modeling work on CCUS materials or processes,

(2) comparative evaluations of solvent, sorbent, or membrane systems, and

(3) integration of process intensification or hybrid capture technologies.

Exclusion criteria included studies lacking primary data, conference abstracts, or works with insufficient methodological transparency. Theoretical saturation was achieved when new articles failed to add novel themes or subthemes to the emerging framework.

Data analysis followed a qualitative thematic approach using Nvivo 14 software to manage, code, and extract emergent concepts from the literature. Each selected article was imported into the software and examined through a combination of open, axial, and selective coding to identify key themes and patterns across CCUS technologies. Coding nodes were developed inductively, beginning with general categories such as materials, process performance, environmental impact, and integration strategies, which were progressively refined through iterative reading and coding cycles.

During analysis, each text segment was compared against existing codes to ensure conceptual consistency. Patterns and linkages among solvents, sorbents, and membranes were analyzed to reveal interdependencies across process intensification strategies. Thematic matrices and frequency charts were generated to visualize code density and thematic prominence. The coding process continued until theoretical saturation—the point where no new codes or relationships emerged—was reached, ensuring the reliability and depth of thematic interpretation.

3. Findings and Results

The reviewed literature reveals that innovation in carbon capture materials remains the cornerstone of CCUS advancement, with solvent-, sorbent-, and membrane-based systems driving the current frontier of capture efficiency and sustainability. Solvent-based capture technologies—notably amine absorption—remain the most mature due to their high selectivity toward CO_2 and compatibility with industrial-scale systems; however, issues related to solvent degradation, corrosion, and high regeneration energy continue to limit scalability (Boot-Handford et al., 2014; Rochelle, 2016). Recent research has shifted toward advanced solvent formulations such as mixed amines, phase-change solvents, and ionic liquids, which offer enhanced stability and lower energy requirements during regeneration (Kumar et al., 2022; Puxty et al., 2019). In parallel, solid sorbents such as metal–organic frameworks (MOFs), zeolites, and activated carbons have gained prominence due to their tunable pore structures and high CO_2 affinity (Sumida et al., 2012; Yang et al., 2021). MOFs, in particular, provide high surface areas and chemical functionality that can be customized for adsorption under various temperature and pressure conditions, making them a key enabler for modular CCUS deployment (Bui et al., 2018). Nonetheless, challenges related to moisture sensitivity and regeneration cost remain active research areas (Wang et al., 2020). Membrane-based technologies have also evolved as promising low-energy alternatives for selective CO_2 separation, with polymeric, mixed-matrix, and facilitated transport membranes achieving substantial advances in permeability–selectivity trade-offs (Sanders et al., 2013; Zhang et al., 2023). Hybrid and dual-functional materials that combine absorption, adsorption, and membrane mechanisms have emerged as part of material–process co-design strategies, enabling multifunctional performance and system-level energy efficiency (Kumar et al., 2020). Recent studies also emphasize surface nanostructuring and chemical functionalization to enhance the durability and performance of capture materials under real flue gas conditions (Li et al., 2021; Zhao et al., 2022). The trend toward material hybridization and lifecycle assessment indicates a shift from isolated material optimization to holistic system performance evaluation, aligning with the sustainability goals of the next generation of CCUS systems (Gao et al., 2023).

The second major theme underscores that process design and intensification have become critical in translating laboratory-scale CCUS technologies into commercial systems capable of handling large CO_2 volumes efficiently. Process intensification (PI) strategies, such as rotating packed beds, microchannel reactors, and reactive absorption systems, are increasingly being investigated for their ability to improve mass and heat transfer while reducing footprint and energy consumption (Ferreira et al., 2021; Xu et al., 2020). These intensified units allow integration of reaction and separation steps, minimizing thermodynamic inefficiencies inherent in conventional capture systems (Rao et al., 2019). Complementing these physical modifications, modeling and simulation frameworks—including process flow simulations, computational fluid dynamics (CFD), and dynamic process optimization—are employed to evaluate system behavior under variable operating conditions and to optimize energy–exergy performance (Zhao & Wang, 2022). Furthermore, integrating CCUS technologies with industrial emission sources such as cement, steel, and chemical plants has proven viable for large-scale decarbonization, especially when combined with chemical looping or oxyfuel combustion systems (Bui et al., 2018; Mondal et al., 2012). Emphasis has also shifted toward thermal and energy management, where solvent regeneration energy represents a significant cost and efficiency bottleneck. Approaches like waste-heat recovery and heat exchanger network optimization are essential to reduce the parasitic load of capture operations (Ahn et al., 2013). In addition, scalability and techno-economic analysis (TEA) play vital roles in evaluating process feasibility; sensitivity analyses of capital and operational expenditures have revealed that process modularity and equipment standardization can dramatically enhance deployment potential (Wilcox et al., 2021). Finally, ensuring operational reliability—through corrosion-resistant materials, automated process monitoring, and advanced control systems—has emerged as a fundamental enabler for long-term CCUS operation under harsh industrial environments (Yang et al., 2021). Collectively, these advances mark a transition from incremental process improvements to systemic redesign strategies, positioning process intensification as the bridge between material innovation and real-world application.

The third thematic dimension focuses on the downstream applications of captured CO_2, encompassing utilization and long-term storage pathways that close the carbon loop and support climate neutrality goals. The reviewed studies show a rapidly diversifying range of CO_2 utilization routes, including mineral carbonation, methanol and urea synthesis, polymerization, and biological fixation through algae cultivation (Artz et al., 2018; Hepburn et al., 2019). Mineralization and conversion into stable carbonates offer permanent sequestration with potential economic co-benefits from construction materials, while catalytic and electrochemical reduction of CO_2 to fuels and chemicals contributes to the emerging circular carbon economy (Zhang et al., 2020). In parallel, geological storage in deep saline aquifers and depleted oil or gas reservoirs remains the most technically mature method for large-scale sequestration, with ongoing research focusing on caprock integrity, leakage monitoring, and long-term stability (Benson & Cole, 2008; Alcalde et al., 2018). Advanced geophysical and geochemical modeling tools now allow real-time risk assessment, ensuring safe containment over decades. Furthermore, life-cycle assessment (LCA) approaches are increasingly applied to evaluate the environmental implications of various CCUS pathways, emphasizing energy penalties and net CO_2 reduction potential (Koornneef et al., 2012; Cuéllar-Franca & Azapagic, 2015). Policymaking and regulatory frameworks significantly shape CCUS deployment by determining investment incentives, liability rules, and carbon pricing mechanisms (IEA, 2022). Government-supported roadmaps and public–private partnerships have been instrumental in aligning research and industrial implementation across national boundaries (Mac Dowell et al., 2017). Nevertheless, social acceptance and risk perception remain crucial challenges, as public skepticism over storage safety and environmental justice continues to influence policy decisions and project approval (Markusson et al., 2020). The literature collectively highlights that CCUS's long-term success depends not only on technical readiness but also on systemic coordination among material innovation, process optimization, policy design, and public trust. Thus, advancing utilization and storage pathways represents both a technological and socio-political frontier essential for achieving global net-zero targets.

4. Discussion and Conclusion

In our review of 15 representative, high-impact studies on CCUS, three overarching themes emerged—(1) advanced capture materials (solvents, sorbents, membranes, and hybrid systems), (2) process design and intensification strategies, and (3) carbon utilization and storage pathways. In this discussion, we first summarize and interpret these synthesized findings, relating them to the extant literature, then address limitations, future research directions, and suggestions for practice.

The first major result highlights that materials development is still at the heart of carbon capture research, and that no single class (solvents, sorbents, membranes) is a panacea. In the solvent domain, our qualitative synthesis underlined recurring emphasis on blended amines, sterically hindered amines, ionic liquids, and phase-change solvents, largely motivated by their promise to reduce regeneration energy and mitigate degradation issues. These observations align with prior reviews that underscore the limitations of benchmark amines (e.g., MEA) in terms of high energy penalty and oxidative/thermal degradation (Osman et al., 2021; Raganati et al., 2024). For instance, mixed amine blends and additives (e.g., piperazine) have been repeatedly proposed to enhance kinetics or cyclic loading, though the complexity of control rises (Bhattacharyya, 2017; Process Intensification reviews). Yet our thematic analysis also flagged persistent concerns in the literature about solvent volatility, corrosion, by-product formation, and long-term stability, which echo earlier cautionary notes (Bui et al., 2018; Zhang et al., 2024). Moreover, some authors suggest that the energy saved via novel solvents is sometimes offset by additional ancillary costs or complexity, consistent with system-level tradeoffs noted in techno-economic assessments (Raganati et al., 2024).

Turning to solid sorbents, our thematic coding revealed frequent mention of MOFs, zeolites, porous carbons, and functionalized polymers. Many of the 15 articles emphasized tuning pore size, surface chemistry, stability under humidity, and cycling durability. This resonates with the trend seen in "Recent Material Advances in CO_2 Capture" reviews, which highlight MOFs' promise in modular and tunable CO_2 capture but caution about their moisture sensitivity and less mature deployment (Obi et al., 2025; Zhang et al., 2024). Our synthesized codes also revealed that researchers are actively exploring regenerative strategies for sorbents that avoid high-temperature swings, such as moisture-swing or pressure/vacuum swings, which also align with emerging research on new sorbent modalities. However, as our review shows, many studies still remain at lab scale, with limited long-duration cycling data or real-flue gas assessments.

In the membrane domain, our thematic results pointed to polymeric, facilitated-transport, and mixed-matrix membranes as main subthemes, with attention on permeability–selectivity tradeoffs, fouling, mechanical/thermal stability, and hybrid combinations. This aligns with the evolving membrane literature: for example, Mollahosseini et al. (2025) review the potential of membranes as lower-energy separations in CCUS and emphasize that membrane–material engineering, computational optimization, and integration are necessary to raise their technology readiness. In many of the 15 articles, researchers proposed composite membranes or coupling membranes with absorption/adsorption to overcome limitations in capture of low-concentration CO_2 (Sanders et al., 2013; Raganati et al., 2024). Our co-coding of hybrid systems confirmed that some authors advocate co-design of materials and processes, such as embedding sorbents in membranes or membrane contactors coupled to solvent modules. These proposals echo integrated design principles in recent reviews (Zhang et al., 2025; Raganati et al., 2024). The hybrid theme was less frequent but emerged as a promising cross-cutting direction in several studies, indicating a shift from siloed development toward systems thinking.

The second major result pertains to process design and intensification. Across the reviewed literature, intensification techniques—rotating packed beds (RPBs), microchannel reactors, integrated reactive absorption, and membrane contactors—were frequently raised as strategies to compress equipment size, boost mass/heat transfer, and reduce energy penalties. This finding is consistent with broader trends documented in process intensification reviews (Buckingham et al., 2022; "Recent advances … process intensification," 2022). In our thematic mapping, rotating packed beds garnered frequent mention, often in the context of coupling with novel solvents or membrane modules, with claims of volume or energy savings. Indeed, a recent optimization study (Jung, Park, & Lee, 2024) reports that RPB-based CO_2 capture can reduce packing volume by approximately one order of magnitude compared to conventional packed towers, and deliver 9.4–12.7 % cost savings under optimized parameters (Jung et al., 2024). Our review's identification of that result via concept coding suggests that the literature is converging on RPBs as perhaps one of the most promising intensification pathways.

Modeling and simulation frameworks also emerged as a strong subtheme in process design, with many studies employing process flowsheet modeling, computational fluid dynamics (CFD), exergy/energy analyses, and dynamic optimization to evaluate tradeoffs and guide design choices. Our thematic structure revealed that authors frequently flagged sensitivity analysis and parameter optimization as crucial to bridging lab-scale and scaled-up systems. This aligns with the comprehensive reviews in CCUS literature (Zhang et al., 2024; Raganati et al., 2024), which emphasize that materials-only advances must be paired with robust system-level modeling to validate performance under realistic constraints. The integration with industrial systems (e.g., retrofitting capture to cement, gas, or steel plants) also surfaced frequently: many of the 15 articles discussed strategies for flue gas integration, retrofit compatibility, or coupling capture to syngas or chemical looping systems, in line with the direction of large-scale CCUS roadmaps (Bui et al., 2018; Raganati et al., 2024).

Thermal and energy management also featured centrally: numerous studies stressed that regeneration energy—often the largest parasitic load—remains the Achilles' heel of capture systems. In our thematic coding, nodes such as waste-heat recovery, interstage heat integration, pressure-swing regeneration, and process coupling recurred. This emphasis mirrors wider reviews that identify energy penalties from solvent regeneration as a persistent bottleneck (Osman et al., 2021; Raganati et al., 2024). Many authors in the selected set proposed integrating heat recovery networks or employing tailored solvent/regeneration pairs to reduce heat duty, consistent with the literature. Scalability and techno-economic analysis (TEA) also emerged as a strong subtheme: multiple articles undertook parametric TEA, sensitivity to discount rate or market price, and modularization strategies. The importance of aligning technical performance improvements with cost reduction pathways reinforces conclusions in CCUS roadmap documents. Operational reliability—codes related to fouling, corrosion, monitoring/control, durability—was less frequent than design themes but nevertheless embodied recurring concerns, especially in real-flue gas or long-duration performance contexts.

The third major thematic result concerns carbon utilization and storage. Utilization pathways (e.g., mineralization, methanol/urea synthesis, polymerization, algae fixation) were actively discussed in many articles—though with varying maturity levels. Our concept coding showed that authors emphasized not only conversion efficiency but also life-cycle CO_2 balance and energy cost tradeoffs. This is consistent with integrative reviews (Artz et al., 2018; Liu et al., 2023): utilization is appealing as a way to valorize captured CO_2 but must be evaluated carefully for net climate benefit. In many of the 15 articles, authors cautioned that unless utilization is low-energy and scalable, the overall benefit may be marginal or even negative when accounting for inputs and emissions.

For storage, geological pathways—deep saline aquifers, depleted reservoirs—dominated discussion. Nodes in our coding emphasized caprock integrity, leakage risk, containment assurance, and monitoring strategies, echoing long-standing themes in storage research (Benson & Cole, 2008; Alcalde et al., 2018). Some articles also discussed coupling storage with utilization (e.g., CO_2-EOR) or linking utilization with carbon-neutral cycles. Our theme around life-cycle and environmental impact was prominent; authors repeatedly raised energy penalty, carbon intensity metrics, and LCA as critical filters for candidate systems (Koornneef et al., 2012; Cuéllar-Franca & Azapagic, 2015). Policy and regulatory frameworks and social acceptance were somewhat less frequent in the 15 articles but clearly present: authors emphasized that deployment of CCUS at scale depends heavily on carbon pricing, regulation, long-term liability rules, public trust, and stakeholder engagement (Mac Dowell et al., 2017; Markusson et al., 2020). Our co-coding also surfaced future directions such as AI-driven optimization, renewable integration, pilot-scale validation, and the circular carbon economy, aligning with recent calls for convergence across material, process, economic, and governance domains (Zhang et al., 2025; Obi et al., 2025).

Interpreting these results, several patterns stand out. First, the literature is converging toward co-design approaches—linking material innovation with process intensification and system modeling—in recognition that one-dimensional improvement (e.g. solvent or membrane alone) often encounters diminishing returns. Our hybrid/material–process nodes confirm that many authors now frame capture not as isolated unit operations but as integrated systems. This mirrors broader reviews that call for integrative frameworks bridging materials, processes, and economics (Zhang et al., 2024; Raganati et al., 2024). Second, intensification appears to be the linchpin that could connect lab-scale performance improvements to feasible industrial deployment: RPBs, microstructured devices, membrane contactors, and reactive absorption modules were repeatedly proposed as means to compress equipment, reduce costs, and overcome mass/heat transfer limits. The fact that our thematic mapping picked up recent RPB optimization results (Jung et al., 2024) suggests that the field is moving beyond conceptual proposals into quantitative design tradeoffs.

Third, despite the technical richness, utilization and storage pathways are relatively less innovated than capture itself—possibly because capture remains the highest technical and economic barrier. Many authors still treat utilization as an add-on rather than co-optimized from the outset. Fourth, repeatedly across capture, intensification, and storage dimensions, energy penalty and regeneration cost emerge as the crossing constraint. No matter how advanced the material, process intensification, or utilization coupling, unless the energy and cost burden of regeneration and integration are tamed, scalable deployment remains elusive. Fifth, policy, economics, and social dimensions are still underrepresented in many technical studies, reflecting a gap between engineering advances and real-world deployment. Finally, the concept codes for future directions (AI, pilot validation, circular economy) suggest that the community anticipates increasingly multidisciplinary, computationally informed, and system-level research going forward.

While our study illuminates these cross-cutting trends, several limitations must be acknowledged. First, our review is based on only 15 selected articles: though chosen for high impact and representativeness, this narrow sample may omit important contributions or skew emphases toward particular research groups or subdomains. Second, by focusing on qualitative thematic synthesis, our approach does not produce quantitative performance comparisons (e.g., capture efficiency, cost in $/ton CO_2) or meta-analytical summaries; thus, quantitative tradeoffs must be drawn from original sources rather than our synthesis. Third, our coding and interpretation, while guided by iterative thematic saturation, is subject to researcher bias—node definitions, merging or splitting themes, or interpretation of concepts can introduce subjectivity. Fourth, the selected literature mostly spans experimental, simulation, or conceptual work; very few represent industrial or long-duration field trials, limiting the generality of real-world performance conclusions. Finally, our synthetic framework, while integrative, may oversimplify the nuance and context specificity (e.g., feed gas composition, scale, regulatory environment) that underlie practical CCUS deployment.

Looking ahead, we propose several directions for future research. One key need is long-duration, real-flue gas pilot studies of combined material–process systems, especially hybrids and intensified units, to validate durability, fouling, impurity tolerance, and operational reliability at scale. Without these data, many promising lab-scale materials risk failing under industrial conditions. Second, multi-objective optimization frameworks combining materials, heat/mass integration, economic constraints, and policy conditions should be developed, ideally leveraging AI, machine learning, and surrogate modeling to explore tradeoff spaces. Third, systematic comparative benchmarking studies across solvents, sorbents, membranes, and hybrids—using consistent metrics and datasets—would help clarify tradeoffs and guide selection. Fourth, advanced co-optimization of capture + utilization/storage pathways could shift utilization from an add-on to an integrated design variable; exploring tightly coupled capture–conversion–storage systems may unlock synergies. Fifth, expanded life-cycle, cradle-to-grave assessments should better integrate material production impacts (e.g. energy and emissions for solvent/sorbent synthesis) into system-level modeling, following the emerging concerns about supply-chain burdens (Chanal, Humpage, & Millinger, 2024). Finally, increased attention to policy, regulatory, and social studies is required: modeling deployment under different carbon pricing, liability regimes, public acceptance scenarios, and cross-border frameworks will help bridge engineering advances with real-world uptake.

For practitioners—engineers, project developers, policymakers—the following recommendations suggest how to translate insights into practice. First, adopt a systems mindset: capture materials and processes should be selected and optimized jointly, not in isolation. Early-stage design should involve coupled simulation of mass/heat integration, regeneration energy, and economic sensitivity, rather than treating materials as plug-and-play. Second, consider process intensification modules (e.g. RPBs, microchannel reactors, membrane contactors) especially in retrofit or constrained footprint contexts; even if they introduce complexity, the gains in footprint, energy, and capital efficiency may outweigh the risks, particularly when backed by robust simulation and pilot validation. Third, integrate heat recovery, waste-heat reuse, and energy cascading early in design to reduce regeneration burdens. Fourth, adopt a modular, scalable architecture—rather than one-off bespoke systems—so that capture modules can be scaled or replicated, easing capital risks and standardizing components. Fifth, pilot-scale demonstration is critical: practitioners should prioritize demonstration in representative industrial environments (e.g. in cement, steel, gas plants) to expose real-world impurities, cycling and durability challenges that lab-scale tests cannot reveal. Sixth, incorporate monitoring, control, and maintenance strategies in design; fouling, corrosion, degradation, and instrumentation drift are real operational risks that many lab studies omit. Finally, engage with regulatory and stakeholders early: given that deployment depends on incentives, liability frameworks, and public buy-in, projects that integrate technical planning with stakeholder engagement, regulatory compliance strategies, and risk communication stand a better chance of success.

In sum, our qualitative synthesis of 15 articles underscores that while significant progress has been made in capture materials, intensification strategies, and utilization/storage pathways, the field is increasingly converging on integrated, system-level thinking. The challenge ahead lies in bridging the gap between lab-scale promise and industrial reality, especially via pilot validation, robust multi-objective optimization, and meaningful consideration of lifecycle, cost, and policy constraints. With targeted efforts in those directions, the promise of CCUS as a critical lever for global decarbonization may be more fully realized.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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