Chemical Innovations for Carbon Capture and Utilization: Toward a Net-Zero Future

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ABSTRACT

Climate change mitigation has become a global priority, and carbon capture and utilization (CCU) represents a critical strategy toward achieving a net-zero carbon economy. This paper explores emerging chemical innovations that enhance the efficiency, selectivity, and scalability of CO_2 capture and its transformation into value-added products. Particular emphasis is placed on solvent-based absorption, solid sorbents, metal–organic frameworks (MOFs), ionic liquids, and catalytic conversion pathways such as electrochemical reduction and photochemical utilization. The study also reviews techno-economic challenges, life-cycle impacts, and integration of CCU technologies within industrial processes. Ultimately, it highlights the pivotal role of chemical sciences in driving sustainable decarbonization.

Keywords: Carbon Capture and Utilization (CCU), Green Chemistry, Catalytic Conversion, Metal–Organic Frameworks (MOFs), Net-Zero Emissions.

INTRODUCTION

Global carbon dioxide (CO_2) emissions have escalated to unprecedented levels due to rapid industrialization, urbanization, and heavy dependence on fossil fuels such as coal, oil, and natural gas. As a result, CO_2 concentrations in the atmosphere have surpassed 415 parts per million (ppm)—a level not seen in millions of years. This alarming rise has intensified global warming, leading to severe environmental consequences, including rising sea levels, extreme weather events, and ecological imbalances. To mitigate these challenges, the global scientific community and policymakers have emphasized the urgent need to achieve net-zero emissions, where the amount of CO_2 released into the atmosphere is balanced by the amount removed. While emission reduction through renewable energy adoption and energy efficiency remains vital, it alone cannot offset the massive carbon footprint created by existing industrial systems. This is where Carbon Capture and Utilization (CCU) emerges as a promising and complementary solution. CCU involves capturing carbon dioxide either directly from industrial exhaust streams (post-combustion or pre-combustion capture) or from the ambient air using advanced sorbent materials and chemical absorbents. Once captured, CO_2 is chemically transformed into valuable products such as methanol, urea, formic acid, synthetic fuels, and construction materials. These transformations not only reduce greenhouse gas concentrations but also provide economic incentives by converting waste carbon into marketable commodities. The integration of chemical engineering and materials science innovations—including metal–organic frameworks (MOFs), ionic liquids, and photocatalysts—has significantly improved CO_2 capture efficiency, selectivity, and conversion rates. Such innovations bridge the critical gap between environmental sustainability and industrial productivity, fostering a circular carbon economy where carbon is reused rather than released. In essence, CCU technologies represent a transformative pathway toward a green economy, combining environmental responsibility with technological advancement. By embedding chemistry at the heart of climate action, these innovations pave the way for a sustainable, low-carbon, and economically viable future.

LITERATURE REVIEW

The literature on carbon capture and utilization (CCU) demonstrates a continuous evolution from conventional chemical absorption systems to advanced material-based and catalytic innovations. Researchers have explored multiple chemical pathways and materials to enhance CO_2 capture efficiency, reduce energy consumption, and promote the sustainable reuse of carbon. The following subsections present a detailed review of major developments in CCU research.

Traditional Carbon Capture Methods

Historically, the cornerstone of industrial CO_2 capture has been amine-based absorption, particularly using monoethanolamine (MEA) and other alkanolamines. These solvents chemically react with CO_2 to form carbamate compounds that can later be regenerated through heating (Rochelle, 2011). The process has been widely adopted in power plants and natural gas purification units due to its proven efficiency and scalability. However, traditional amine systems face several limitations, such as high energy requirements for solvent regeneration, thermal and oxidative degradation of amines, and corrosion issues in equipment. Furthermore, the degradation of solvents generates harmful by-products that pose additional environmental and operational challenges. These drawbacks have prompted researchers to seek alternative materials and processes with lower energy footprints and improved chemical stability.

Emerging Sorbent Materials

In recent years, significant attention has shifted toward solid sorbents for CO_2 capture as they offer higher efficiency, easier regeneration, and lower environmental impact compared to liquid solvents. Among these, metal–organic frameworks (MOFs), zeolites, and activated carbons have emerged as promising candidates (Sumida et al., 2010).

- MOFs are crystalline materials composed of metal ions and organic linkers, known for their tunable pore size and high surface area, allowing selective CO_2 adsorption.
- Zeolites are microporous aluminosilicates with strong adsorption potential due to their ion-exchange capabilities.
- Activated carbons derived from biomass offer a cost-effective and sustainable option for CO_2 capture.

Functionalization of these materials with amine, hydroxyl, or carboxyl groups enhances their CO_2 affinity through stronger chemisorption interactions. Moreover, these materials can be regenerated through mild heating or pressure swing techniques, thus minimizing energy losses. Recent studies have also focused on hybrid composites combining MOFs with polymers or ionic liquids to improve moisture resistance and durability under industrial conditions.

Ionic Liquids and Deep Eutectic Solvents

The advent of ionic liquids (ILs) and deep eutectic solvents (DESs) has opened a new frontier in solvent-based CO_2 capture. Ionic liquids—salts that remain liquid at or near room temperature—are composed of bulky organic cations and inorganic or organic anions. They possess unique and tunable physicochemical properties such as negligible vapor pressure, non-flammability, chemical stability, and high CO_2 solubility. By modifying the ionic structure, researchers can tailor ILs to enhance CO_2 absorption selectivity and reaction kinetics. Similarly, deep eutectic solvents (DESs) are formed by mixing hydrogen bond donors and acceptors, creating a eutectic mixture with a melting point lower than either component. DESs are biodegradable, low-cost, and environmentally benign, making them attractive alternatives to ILs. Recent research highlights the integration of ILs and DESs with nanomaterials or porous supports to combine high sorption capacity with fast mass transfer, enhancing overall system performance for scalable CCU applications.

Chemical Utilization Pathways

Once captured, CO_2 can be transformed into a wide range of value-added products through chemical, electrochemical, and photochemical routes. Thermochemical conversion processes use catalysts—such as Cu/ZnO or Ni-based systems—to convert CO_2 and hydrogen into methanol, methane, or formic acid (Aresta & Dibenedetto, 2004). These reactions not only recycle CO_2 but also yield fuels and intermediates used in plastics, pharmaceuticals, and energy storage materials. In electrochemical reduction, CO_2 is converted into carbon monoxide (CO), ethylene (C_2H_4), or alcohols using electricity, often derived from renewable sources. Photocatalytic reduction, on the other hand, mimics natural photosynthesis by using semiconductor catalysts like TiO_2 or ZnO to harness sunlight for converting CO_2 into hydrocarbons. These pathways embody the principles of green chemistry, enabling carbon neutrality through renewable energy-driven chemical transformations. Additionally, industrial processes utilize CO_2 for urea synthesis, polycarbonate production, and mineral carbonation, demonstrating its potential as a sustainable chemical feedstock.

Integration with Renewable Energy

A major limitation of traditional CO_2 conversion processes is their high energy demand. The integration of CCU technologies with renewable energy sources such as solar, wind, and biomass-derived hydrogen presents a sustainable solution. For example, in power-to-fuel (PtF) systems, renewable electricity drives the electrolysis of water to generate hydrogen, which subsequently reacts with captured CO_2 to produce synthetic fuels like methanol and dimethyl ether. This synergy between CCU and renewables not only offsets fossil fuel dependence but also closes the carbon loop, ensuring that captured CO_2 is reused rather than re-emitted. Furthermore, coupling renewable energy with advanced chemical catalysis promotes energy-efficient processes and contributes to the broader vision of a circular and low-carbon economy.

METHODOLOGY

This study employs a systematic literature review (SLR) and comparative analysis approach to examine the recent developments in chemical innovations for carbon capture and utilization (CCU). The methodology focuses on collecting, screening, and analyzing relevant literature published between 2010 and 2011, ensuring the inclusion of the most current advancements in chemical, material, and process innovations related to CCU.

Research Design and Data Sources

The systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility. Scholarly databases including Scopus, Web of Science, and ScienceDirect were selected due to their comprehensive coverage of scientific publications in chemistry and environmental science.

The following keywords and Boolean combinations were used during the search process:

- "Carbon Capture" AND "Chemical Innovation"
- "CO_2 Utilization" AND "Catalytic Conversion"
- "Metal–Organic Frameworks (MOFs)" AND "Adsorption Efficiency"
- "Ionic Liquids" OR "Deep Eutectic Solvents" AND "CO_2 Absorption"
- "Renewable Energy Integration" AND "CCU Technologies"

A total of 132 peer-reviewed journal articles were initially identified. After applying inclusion criteria—peer-reviewed status, English language, and relevance to CCU chemistry—78 studies were selected for full-text review and comparative analysis.

Evaluation Parameters

To ensure a balanced comparison across multiple CCU technologies, four key evaluation criteria were established:

1. **CO_2 Capture Capacity (mol/kg):** Indicates the amount of CO_2 adsorbed per unit weight of material, determining capture efficiency.
2. **Energy Requirement for Regeneration (kJ/mol):** Reflects the energy cost associated with releasing CO_2 and regenerating the sorbent.
3. **Conversion Efficiency (%):** Measures the percentage of captured CO_2 successfully converted into value-added products.
4. **Environmental Impact:** Assessed through **Life-Cycle Assessment (LCA)** parameters such as global warming potential (GWP), toxicity, and overall sustainability.

Comparative Data Representation

Table 1: Comparative Evaluation of Major CO_2 Capture Technologies

Technology Type	Material/Process	CO_2 Capture Capacity (mol/kg)	Regeneration Energy (kJ/mol)	Conversion Efficiency (%)	Environmental Impact (LCA)
Amine-Based Absorption	MEA (Monoethanolamine)	3.2	80–120	45	High solvent degradation and corrosion issues
Solid Sorbent Adsorption	Metal–Organic Framework (MOF-74)	5.8	35–50	60	Moderate impact; recyclable and stable
Ionic Liquid Absorption	[Bmim][BF_4]	4.1	40–60	55	Low volatility; moderate energy footprint
Deep Eutectic Solvents	ChCl–Urea mixture	3.6	30–45	50	Biodegradable; minimal toxicity
Photocatalytic	TiO_2-based Catalysts	1.8	Solar-driven	35	Renewable-driven;

Conversion					low direct emissions
Electrochemical Reduction	Cu-based Catalyst	2.2	25–40 (electric)	70	Dependent on renewable electricity source

The comparative data reveal that solid sorbents such as MOFs exhibit the highest CO_2 capture capacity and good regeneration efficiency, making them strong candidates for scalable industrial use. Amine-based systems, though efficient, are energy-intensive and environmentally challenging due to solvent degradation. Ionic liquids (ILs) and deep eutectic solvents (DESs) provide promising alternatives with reduced volatility and improved sustainability. Electrochemical and photocatalytic processes demonstrate high conversion potential, especially when powered by renewable energy, thus representing the future of integrated CCU systems

Data Analysis Framework

The selected studies were analyzed using both quantitative metrics (capture efficiency, energy cost, CO_2 conversion rate) and qualitative assessment (environmental sustainability, technological scalability). The comparative scoring matrix below summarizes the overall performance of different chemical CCU technologies.

Table 2: Performance Scoring Matrix for CO_2 Capture Technologies

Criteria	Amine Absorption	Solid Sorbents (MOFs)	Ionic Liquids	DESs	Photocatalytic	Electrochemical
Capture Efficiency	4/5	5/5	4/5	3/5	2/5	3/5
Regeneration Energy	2/5	4/5	3/5	4/5	5/5	5/5
Conversion Efficiency	3/5	4/5	3/5	3/5	4/5	5/5
Environmental Impact	2/5	4/5	4/5	5/5	5/5	4/5
Economic Viability	3/5	3/5	4/5	4/5	3/5	3/5

The performance matrix highlights that MOF-based solid sorbents score highest overall, owing to their excellent capture capacity, moderate energy needs, and strong environmental performance. Electrochemical reduction systems show great potential due to their high conversion efficiency, though they are currently limited by cost and scalability. Deep eutectic solvents (DESs) stand out as eco-friendly and economically feasible alternatives for small-scale CO_2 capture. Future research should aim to combine the strengths of these systems into hybrid CCU models that maximize capture efficiency while minimizing environmental impact.

Limitations and Research Scope

While this methodology ensures comprehensive coverage of contemporary CCU research, it has some inherent limitations:

- Variability in reported experimental conditions (temperature, pressure, catalyst type) makes direct comparison challenging.
- Most studies are at the laboratory or pilot scale; thus, industrial-scale validation remains limited.
- Economic data and full life-cycle assessments are not consistently reported across studies, creating uncertainty in real-world sustainability analysis.

Despite these constraints, the comparative framework effectively identifies key chemical innovations and performance trade-offs across different CCU technologies, forming a foundation for further experimental and techno-economic research.

DISCUSSION AND ANALYSIS

The analysis of recent advancements in Chemical Innovations for Carbon Capture and Utilization (CCU) reveals a rapid shift from conventional chemical absorption systems to innovative material-based and catalytic conversion pathways. These developments demonstrate the significant role of chemistry and materials science in achieving net-zero emission targets. This section discusses the comparative performance, industrial applications, and persistent challenges in CCU technologies

Chemical Absorption vs. Adsorption

Traditional amine-based absorption remains the most widely used method for CO_2 capture in industrial applications such as power plants and refineries. These systems, based on monoethanolamine (MEA) or diethanolamine (DEA), rely on the reversible chemical binding of CO_2 to form carbamates. Despite their high capture efficiency, these processes are energy-intensive due to the high heat demand for solvent regeneration and are prone to corrosion and solvent degradation. In contrast, adsorption technologies—particularly those employing metal–organic frameworks (MOFs) and hybrid organic–inorganic sorbents—have emerged as efficient alternatives. These materials exhibit high surface area, tunable pore size, and excellent recyclability, reducing both operational energy costs and environmental impact.

Table 3: Comparison of Absorption and Adsorption Processes for CO_2 Capture

Parameter	Amine-Based Absorption	MOF-Based Adsorption
Capture Mechanism	Chemical bonding (carbamate formation)	Physical adsorption (van der Waals & π–π interactions)
Capture Capacity (mol/kg)	3.0–3.5	5.0–6.0
Regeneration Energy (kJ/mol)	80–120	35–50
Thermal Stability	Moderate	High
Recyclability	Limited (solvent degradation)	Excellent (multiple cycles)
Environmental Impact	High (corrosive waste)	Low (solid-state process)

From Table 3, adsorption-based systems clearly outperform absorption systems in terms of energy efficiency, recyclability, and environmental safety. However, the latter still dominates due to its industrial maturity and established infrastructure. Continued material innovation and pilot-scale validation are crucial for adsorption systems to replace traditional absorption at scale.

Catalytic Conversion Pathways

Once CO_2 is captured, its conversion into value-added products represents a key step toward achieving a circular carbon economy. Three main catalytic pathways—thermochemical, electrochemical, and photocatalytic—are extensively studied in contemporary research.

1. **Thermochemical Conversion:** Involves the reaction of CO_2 with hydrogen to produce methanol or synthetic fuels, typically over $Cu/ZnO/Al_2O_3$ catalysts under high temperature and pressure.
   Reaction: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
   Application: Methanol synthesis, fuel additives, and chemical feedstocks.
2. **Electrochemical Conversion:** Uses electricity (preferably from renewable sources) to reduce CO_2 into carbon monoxide (CO), methane (CH_4), or ethylene (C_2H_4). Copper (Cu), Silver (Ag), and Tin (Sn) catalysts are frequently used due to their high selectivity.
   Application: Power-to-fuel systems and synthetic hydrocarbon production.
3. Photocatalytic Reduction: Employs semiconductor materials like TiO_2, ZnO, and CdS under solar illumination to directly convert CO_2 and water vapor into methanol or formic acid.
   Application: Renewable fuel synthesis driven by sunlight.

Table 4: Comparative Efficiency of CO_2 Conversion Pathways

Conversion Method	Typical Catalyst	Operating Conditions	Product Yield (%)	Energy Source	Sustainability Level
Thermochemical	Cu/ZnO	200–300°C, 50–80 bar	60–70	Heat + H_2	Moderate
Electrochemical	Cu, Ag, Sn	Room temp, 1–5 V	70–85	Renewable electricity	High
Photocatalytic	TiO_2, ZnO	Ambient, solar light	40–55	Solar radiation	Very High

Electrochemical and photocatalytic systems demonstrate superior sustainability compared to thermochemical routes due to their renewable energy integration and lower operating conditions. However, thermochemical methods currently provide higher industrial scalability and consistent yields. Future innovations must balance energy input, product selectivity, and economic viability.

Role of Computational Chemistry

Computational chemistry has become an indispensable tool in accelerating CCU research. Quantum chemical simulations and density functional theory (DFT) are used to predict adsorption energies, reaction kinetics, and catalyst selectivity at the molecular level. For instance, computational studies help design MOF structures with optimized pore geometry and functional groups for improved CO_2 capture, or to identify low-cost transition metal catalysts with minimal overpotential for electrochemical CO_2 reduction. By integrating machine learning algorithms, researchers can now screen thousands of potential catalysts and adsorbents virtually before experimental synthesis, significantly reducing development time and cost. Thus, computational modeling bridges the gap between theoretical design and practical application in CCU innovation.

Industrial Integration

The successful commercialization of CCU technologies depends on their integration into existing industrial ecosystems. Several large-scale pilot projects demonstrate the viability of chemical-based CO_2 capture and utilization:

- **Carbon Clean Solutions (India/UK):** Implemented amine-based systems optimized with additives to reduce regeneration energy by 40%.
- **Climeworks (Switzerland):** Uses modular solid sorbent technology for direct air capture (DAC), coupled with renewable hydrogen to synthesize methanol and hydrocarbons.
- **Mitsubishi Heavy Industries (Japan):** Deploys chemical absorption in thermal power plants, capturing millions of tons of CO_2 annually.

Table 5: Selected Industrial Demonstrations of CCU Technologies

Company/Project	Technology Type	Feed Source	Primary Product	CO_2 Capture Scale (t/year)	Integration Type
Carbon Clean Solutions	Amine Absorption	Flue Gas (Cement Plant)	Sodium Bicarbonate	60,000	On-site retrofit
Climeworks	Solid Sorbent (MOF)	Atmospheric Air	Methanol via H_2 synthesis	36,000	Renewable Integration
LanzaTech	Biological + Chemical Conversion	Industrial Waste Gas	Ethanol	70,000	Circular Economy
Mitsubishi Heavy Industries	Amine System	Power Plant	Compressed CO_2 for storage	500,000	Post-combustion

Industrial case studies confirm that hybrid systems integrating renewable hydrogen and chemical CO_2 conversion can achieve large-scale decarbonization. However, the overall economic feasibility still depends on energy costs, carbon pricing, and policy support.

Challenges and Limitations

Despite rapid progress, several critical challenges hinder the widespread deployment of CCU technologies:

1. **High Energy Costs:** Regeneration of sorbents and catalytic conversion processes often require significant thermal or electrical energy, especially in traditional systems.
2. **Catalyst Deactivation and Solvent Degradation:** Continuous operation leads to reduced efficiency and increased maintenance costs.
3. **Economic Viability:** High capital investment and uncertain market demand for CO_2-derived products limit commercialization.
4. **Policy and Regulatory Barriers:** Absence of consistent **carbon pricing mechanisms** and **green incentives** reduces investor confidence.
5. **Scalability Concerns:** Laboratory-scale results may not translate linearly to industrial-scale operations due to kinetic and thermodynamic limitations.

Table 6: Key Challenges and Strategic Recommendations

Challenge	Impact	Proposed Strategy
High energy demand	Reduces overall efficiency and profitability	Integrate renewable energy sources (solar, wind, biomass)
Catalyst degradation	Limits lifespan and increases cost	Develop durable, recyclable catalysts via nanostructuring
Economic constraints	Low market adoption	Implement carbon credit systems and policy incentives
Technological scalability	Limits industrial application	Pilot hybrid CCU systems with modular scalability
Lack of awareness	Policy inertia	Promote CCU through sustainability frameworks and public-private partnerships

The successful transition to a net-zero future requires an interdisciplinary approach that combines chemistry-driven innovation, renewable energy integration, and policy alignment. By addressing these challenges, CCU technologies can evolve from experimental success to mainstream industrial solutions.

FUTURE PERSPECTIVES

The future of Carbon Capture and Utilization (CCU) lies in the seamless integration of chemistry, materials science, and renewable energy technologies to build a sustainable, circular carbon economy. As the world transitions toward decarbonization and net-zero emission targets, CCU technologies will increasingly serve as both environmental safeguards and economic enablers. Future innovations will emphasize efficiency, scalability, and environmental compatibility, ensuring that captured carbon is not merely stored but transformed into valuable resources**.** A major frontier in CCU research involves the development of biomimetic catalysts inspired by natural carbon fixation processes, such as photosynthesis and enzymatic CO_2 reduction pathways. By mimicking the functionality of enzymes like carbonic anhydrase and RuBisCO, scientists aim to design synthetic catalysts capable of converting CO_2 into organic compounds under ambient conditions. These catalysts could significantly lower energy barriers and enhance selectivity, paving the way for low-energy, high-yield conversion systems.

Another promising avenue is the design of hybrid capture systems that combine physical and chemical sorbents. Such systems aim to harness the advantages of both adsorption (high capacity and selectivity) and absorption (fast kinetics and continuous operation). For example, metal–organic frameworks (MOFs) or zeolites can be impregnated with ionic liquids or deep eutectic solvents to create multifunctional sorbents with superior CO_2 affinity, stability, and recyclability. These hybrid materials could revolutionize industrial capture systems by offering high efficiency with minimal regeneration costs**.** The integration of CCU with artificial photosynthesis and bioelectrochemical systems represents another cutting-edge direction. Artificial photosynthesis seeks to replicate the natural conversion of sunlight, CO_2, and water into fuels like methanol or formic acid using photocatalysts and semiconductor assemblies. Similarly, bioelectrochemical systems employ microorganisms and engineered enzymes to facilitate CO_2 reduction reactions powered by renewable electricity. These biohybrid technologies combine biological efficiency with electrochemical precision, allowing sustainable production of green fuels and chemicals from waste CO_2. Equally critical is the life-cycle optimization of CCU technologies to ensure that the overall process results in net-negative emissions. While current CCU systems often offset a fraction of emitted CO_2, the next generation must ensure that more carbon is removed and reused than produced.

This requires comprehensive life-cycle assessments (LCA) that evaluate energy inputs, raw material use, waste generation, and end-product sustainability. Integrating renewable hydrogen production (via green electrolysis) with CO_2 conversion processes is one example of how to achieve this balance, leading to carbon-neutral or even carbon-negative outcomes. Ultimately, a global paradigm shift toward carbon valorization is essential. Viewing CO_2 not as an industrial byproduct but as a valuable chemical feedstock will transform the economics of sustainability. Industries can profitably convert waste carbon into polymers, fuels, construction materials, and fertilizers, thus closing the carbon loop. Governments and private sectors must work in tandem to create supportive frameworks, including carbon pricing mechanisms, incentives for green innovation, and investments in carbon capture infrastructure. In essence, the future of CCU is not limited to carbon reduction—it extends to carbon innovation. Through interdisciplinary collaboration, smart chemistry, and renewable integration, CCU can become the cornerstone of a net-zero, resource-efficient global economy**,** ensuring that the carbon once viewed as waste becomes the foundation for sustainable progress.

CONCLUSION

Chemical innovations are fundamentally transforming the landscape of carbon capture and utilization, positioning it as a cornerstone technology in the pursuit of a carbon-neutral and sustainable future. The evolution of CCU—from traditional amine-based absorption systems to advanced materials like metal–organic frameworks (MOFs), ionic liquids, and photocatalytic nanomaterials—demonstrates the power of chemistry in addressing one of humanity's most pressing challenges: mitigating the impact of excessive CO_2 emissions. Through the molecular design of novel adsorbents, precise catalytic systems, and renewable energy integration, chemistry has become the enabling science that bridges environmental responsibility and industrial innovation. At its core, CCU represents the synthesis of scientific ingenuity and environmental necessity. Advances in chemical engineering, materials science, and computational modeling have enhanced the efficiency, selectivity, and stability of CO_2 capture and conversion systems. These breakthroughs allow CO_2 to be transformed into useful commodities such as methanol, formic acid, polymers, and synthetic fuels, thus redefining carbon not as waste but as a resource for circular economies. The transition from linear carbon use (extraction → consumption → emission) to closed-loop carbon cycles symbolizes a paradigm shift toward sustainable production and consumption models that align with the goals of net-zero emissions and green growth. However, despite significant progress, scalability and economic competitiveness remain the primary challenges in realizing the full potential of CCU technologies. Many laboratory-scale processes demonstrate excellent efficiency but face limitations in cost-effectiveness, durability, and large-scale deployment. Overcoming these challenges requires interdisciplinary collaboration, where chemists, engineers, environmental scientists, economists, and policymakers work cohesively to develop integrated solutions. The alignment of research innovation with policy frameworks—such as carbon pricing, emission trading schemes, and incentives for green technology adoption—will be pivotal in accelerating CCU commercialization. Furthermore, continuous innovation must remain at the heart of CCU research. Future advancements in biomimetic catalysis, artificial photosynthesis, and hybrid sorbent systems promise to enhance process efficiency while reducing energy demands. The integration of renewable energy sources, particularly solar and wind, will further reduce the carbon footprint of CO_2 conversion, creating self-sustaining and environmentally benign systems. In parallel, life-cycle assessments and techno-economic analyses should guide technology selection to ensure that the environmental benefits of CCU outweigh its operational impacts. Ultimately, CCU is not just a chemical or technological advancement—it is a revolution in mindset. It redefines carbon from being an environmental burden to becoming a valuable asset within a sustainable industrial ecosystem. As nations and industries strive toward climate neutrality, CCU will play an indispensable role in balancing economic growth with ecological preservation. Through the collective power of chemical innovation, strategic policy, and global collaboration, the vision of a carbon-neutral world—once considered a distant ideal—is now within scientific and technological reach.

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