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Review

Direct Air Capture of Carbon Dioxide: Advances, Feasibility, and Future Directions

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Abstract: Direct air capture technologies have gained prominence as vital tools for atmospheric carbon dioxide removal, with four major categories, namely liquid solvent-based, solid sorbent-based, electrochemical, and emerging hybrid systems, demonstrating varying degrees of maturity and feasibility. Liquid solvent-based direct air capture, including systems using potassium hydroxide, amines, and advanced ionic liquids or deep eutectic solvents, benefits from high CO_2 reactivity and established chemical regeneration processes, but faces limitations from high thermal energy demands, solvent degradation, and environmental handling concerns. Solid sorbent-based systems, such as those utilizing amine-functionalized materials or metal-organic frameworks, offer low-temperature regeneration and modular designs, yet often suffer from variable adsorption capacity under different humidity levels and degradation over multiple cycles. Electrochemical direct air capture is a rapidly advancing field that uses redox-active materials or ion-exchange membranes to reversibly bind and release CO_2 using electrical energy. These systems enable operation under ambient conditions with high selectivity and reduced thermal input, though challenges persist in terms of redox material stability and scalability. Other emerging methods, such as cryogenic, photocatalytic, mineralization-based, and biological direct air capture, offer innovative pathways to reduce energy use or permanently sequester CO_2, but remain at early developmental stages. While significant advances have improved energy efficiency, cost-effectiveness, and operational stability across direct air capture technologies, further research is needed to enhance long-term material performance, develop low-cost, scalable reactor designs, and improve integration with renewable energy systems. Future studies should prioritize techno-economic assessments, lifecycle analysis, and hybrid approaches that combine the strengths of multiple direct air capture pathways to achieve cost-effective and durable carbon removal at gigaton scales.

***Keywords*:** climate change, direct air capture, electrochemical, liquid solvent, renewable energy, solid sorbent

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has emphasized the urgent need to cut global greenhouse gas emissions by 2030 and to achieve net-zero emissions by 2050.[1] Among all greenhouse gases, the accumulation of carbon dioxide in the atmosphere is widely acknowledged as the primary driver of climate change.[2] According to the Global Carbon Budget 2024, global carbon dioxide emissions from fossil fuel combustion have increased steadily, rising from around 11 billion metric tons annually in the 1960s to an estimated 37.4 billion metric tons in 2024.[3] This upward trajectory poses a serious threat to climate targets. To limit global warming to below 1.5 °C, the IPCC recommends a

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reduction of approximately 45% in carbon dioxide emissions by 2030 compared to 2010 levels, which were estimated at 410 $GtCO_2$.[1] Achieving this target requires not only a rapid transition away from fossil fuels but also the deployment of technologies capable of removing CO_2 from the atmosphere, such as carbon capture, utilization, and storage.[4,5]

In this context, direct air capture has gained increasing attention as a novel and potentially transformative approach to addressing climate change. Although still in its early stages of commercialization, direct air capture is recognized as a promising technology for negative emissions.[6] Direct air carbon capture involves capturing carbon dioxide directly from ambient air using chemical or physical methods, and this is often followed by its permanent storage in geological formations.[7] This approach is particularly valuable because it can help offset emissions from dispersed or hard-to-abate sources and may play a key role in achieving long-term climate targets.

Direct air capture systems operate primarily through absorption or adsorption processes. In absorption-based systems, carbon dioxide is captured using liquid solvents, typically aqueous alkaline solutions. Adsorption-based systems, on the other hand, use solid materials such as amine-functionalized sorbents or Metal-Organic Frameworks (MOFs).[8] Adsorption processes tend to require lower regeneration temperatures (typically 70-100 °C), which can often be supplied by low-grade heat, making them potentially more energy-efficient. In contrast, regenerating carbon dioxide from solvent-based systems often demands high temperatures, around 900 °C, making them more energy-intensive.[7,9] Extensive research has been devoted to improving both categories of direct air capture technology, including high-temperature aqueous absorption systems and low-temperature solid sorbent systems.[10,11]

Despite growing optimism, the real-world viability of direct air capture remains contested. While many researchers see it as an essential component of future climate mitigation portfolios, others caution that it may be overhyped. A multi-model analysis by Realmonte et al.[12] suggests that direct air capture could significantly reduce overall mitigation costs if scaled rapidly to remove approximately 1.5 gigatons of carbon dioxide per year by 2100. However, critics such as Chatterjee and Huang[13] argue that such projections overlook major barriers, including the massive energy requirements, limited availability of scalable sorbent materials, and substantial financial investments needed. They contend that a more realistic and cost-effective pathway may lie in aggressively expanding renewable energy systems, rather than relying on large-scale deployment of still-developing direct air capture and storage technologies.

While some researchers highlight direct carbon capture as an essential element of deep decarbonization strategies, working in tandem with electrification and energy storage, others argue that prioritizing renewable energy remains the most cost-effective path for climate mitigation. For example, Bistline and Blanford[14] conducted a power sector analysis indicating that direct air carbon capture could make a meaningful contribution to decarbonization efforts in the United States while requiring less than 5% of the nation's projected electricity demand.

Despite this potential, many analysts suggest that mitigation strategies should initially focus on scaling up renewable energy systems rather than relying on negative-emission technologies, such as direct air capture, particularly under most cost-optimization models.[15,16] However, Supekar et al.[17] argue that the widespread adoption of emission prevention measures, especially in systems dominated by natural gas, could significantly lower the economic barriers to deploying direct air carbon capture and other negative emission technologies by reducing the volume of CO_2 needing removal and thereby improving overall system efficiency. Given the ongoing controversy, it is useful to review the latest direct air capture technologies and assess their feasibility to identify the most effective options with significant environmental advantages. Currently, few reviews address direct air capture of CO_2. Sun et al.[18] examined recent progress in direct air carbon capture, emphasizing adsorption techniques, but did not explore other methods like electrochemical approaches. Their review focuses on how adsorbents capture carbon but offers limited insights into the feasibility. Likewise, Erans et al.[19] concentrated on sorption. Studies by Findley and Sholl[20] and Chen et al.[21] explore metal-organic frameworks specifically for atmospheric CO_2 capture. Zhang et al.[22] investigated the application of porous sorbents for direct air carbon capture.

Unlike previous reviews, this one aims to comprehensively cover the topic by systematically presenting a broad range of technologies for direct air capture of CO_2 and assessing their feasibility. It concludes with suggestions for future research directions. This review facilitates the evaluation of the role of direct air capture within the climate solution portfolio, guides research and development investments, supports responsible deployment, and informs policy development.

2. Review methodology

This review adopts a narrative approach to synthesize recent advancements, feasibility, and future research directions in the field of direct air capture of carbon dioxide. A comprehensive literature search was conducted across multiple academic databases, including Scopus, Web of Science, and ScienceDirect. The search encompassed peer-reviewed journal articles, conference proceedings, and authoritative reports published between 2015 and 2025. Keywords used in the search included direct air capture, carbon dioxide removal, negative emission technologies, CO_2 sorbents, solid sorbents, liquid solvents, electrochemical methods, and emerging CO_2 capture technologies. Combinations of keywords, such as solid sorbent direct air capture, liquid solvents for carbon dioxide removal, and electrochemical negative emission technologies, were used to refine the search.

Studies were included if they met one or more of the following criteria: (1) presented original experimental or modeling data on direct air capture technologies; (2) conducted techno-economic or life-cycle assessments of direct air capture systems; and (3) proposed or evaluated novel materials or process designs for direct air capture. Exclusion criteria included: (1) studies focusing exclusively on point-source carbon capture (e.g., post-combustion carbon capture); (2) studies on carbon storage and utilization without addressing carbon capture; and (3) articles lacking peer review. A qualitative thematic synthesis was employed to structure the review across three dimensions, namely technological advances, feasibility and future research directions.

Over the past decade, research on direct air capture of carbon dioxide has witnessed a marked increase, reflecting growing scientific and policy interest in negative emissions technologies. A bibliometric analysis conducted using Scopus and Web of Science databases revealed the following key trends:

- Publication growth: Annual scientific publications related to direct air capture have grown from fewer than 30 articles in 2015 to over 250 articles in 2024, marking a nearly tenfold increase.
- Leading journals: The majority of studies related to direct air capture have appeared in journals such as Environmental Science & Technology, Joule, Nature Communications, Energy & Environmental Science, and Frontiers in Climate. Engineering and chemical journals like Chemical Engineering Journal and Industrial & Engineering Chemistry Research have also seen a growing share of direct air capture content.
- Top contributing countries: The United States, Germany, the United Kingdom, Switzerland, and China are the leading contributors to direct air capture research, with the United States producing nearly 40% of the total publications.

3. Direct air capture technologies and recent advances

3.1 *Liquid solvent-based systems*

3.1.1 *Advances*

Liquid solvent-based systems represent one of the most mature and widely studied approaches for direct air capture of CO_2. These systems typically use aqueous alkaline solutions, such as potassium hydroxide (KOH), sodium hydroxide (NaOH), or amine-based solvents, to chemically absorb CO_2 from ambient air, forming carbonate or bicarbonate compounds (Figure 1).[23] For instance, the chemical reactions between KOH and CO_2 are shown below:

$$CO_2 \text{ absorption: } CO_2\ (g) + KOH\ (aq) \rightarrow KHCO_3\ (aq)$$

Further reaction at higher KOH concentrations or elevated pH:

$$KHCO_3\ (aq) + KOH\ (aq) \rightarrow K_2CO_3\ (aq) + H_2O\ (l)$$

$$\text{Overall: } CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O$$

The appeal of liquid solvents lies in their high reactivity with CO_2 and their potential for continuous operation through established chemical regeneration methods. Among the most prominent configurations is the use of strong bases like KOH, which can effectively capture low-concentration CO_2 (approximately 420 ppm in ambient air), followed by regeneration through high-temperature calcination in a closed-loop cycle (Figure 1).[24] While this method is chemically robust and capable of achieving high capture efficiency, it suffers from significant limitations, including high energy consumption for solvent regeneration, substantial capital costs for high-temperature equipment (e.g., kilns), slow absorption kinetics due to the low CO_2 concentration in air, and the potential for solvent degradation or environmental handling challenges.[23]

Amine-based solvents are widely used in direct air capture due to their strong chemical affinity for CO_2. In this process, ambient air is passed over a liquid solvent containing amines such as monoethanolamine or other primary and secondary amines, which react with CO_2 to form carbamates or bicarbonates. The CO_2-rich solvent is then heated to release concentrated CO_2 gas and regenerate the amine for reuse (e.g., approximately 4.0 MJ per kg CO_2) (Figure 1).[25,26] This approach benefits from relatively fast CO_2 absorption kinetics and well-established chemical engineering principles, making it one of the more mature direct air capture technologies. However, it faces several limitations: amines are prone to oxidative and thermal degradation, especially under prolonged exposure to air and high regeneration temperatures, leading to reduced solvent lifespan and increased operational costs. Additionally, the regeneration step requires significant thermal energy (often > 3 GJ per ton of CO_2), contributing to high energy demands. Amine systems may also pose environmental and health concerns due to solvent volatility and degradation by-products, necessitating careful handling and emission control.[25,27] These factors collectively hinder the scalability and cost-effectiveness of the process for gigaton-scale carbon removal.

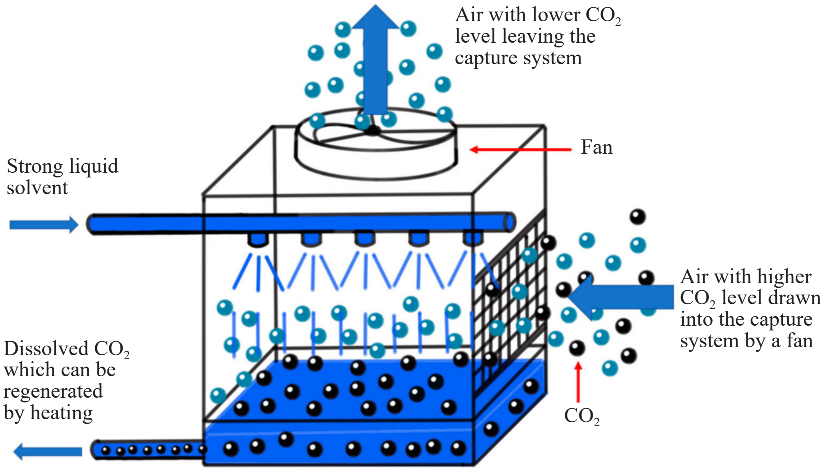

Figure 1. A liquid solvent-based system for direct CO_2 capture from air[28]

Recent advances focus on addressing these limitations. Ionic liquids have shown excellent effectiveness in capturing and separating CO_2 due to their distinctive characteristics and molecular configurations, such as strong stability, extremely low volatility, customizable design, and high solubility and selectivity for CO_2.[29] Recker et al.[30] presented the first laboratory-scale demonstration of using ionic liquids for direct CO_2 capture from ambient air. The ionic liquids, synthesized from bio-derived sources, offer an ideal environment for carbon capture due to their inherent non-volatility and low toxicity. Specifically, liquid salts created from a blend of three branched-chain amino acids, namely valine, leucine, and isoleucine, showed strong potential as reversible CO_2 absorbents (a mole ratio of 1 CO_2 to 2 ionic liquid), effectively capturing carbon dioxide even at the low concentrations present in the atmosphere. These amino acids, typically obtained from biological waste such as feathers, fur, or human hair, make the process particularly appealing by integrating carbon capture with waste valorization.[30] This approach highlights a promising path for sustainable CO_2 capture using renewable, low-impact materials.

Hospital-Benito et al.[31] investigated the application of ionic liquids for direct air capture, identifying [P66614][Im] as the most efficient candidate in terms of both exergy (5.44-16.73 MJ/kg) and energy use (15.15-35.42 MJ/kg), while maintaining a comparable CO_2 capture productivity of 0.5-1.3 kg/(m^3·h). This performance is largely attributed to its superior cyclic CO_2 loading capacity (0.3-0.6 mol/kg). The minimum exergy demand of the [P66614][Im]-based system was found to be marginally lower than that of conventional alkali-based scrubbing (6.21 MJ/kg) and comparable to amine-based systems (5.59 MJ/kg). Moreover, the analysis suggests that, with reasonable assumptions for energy and capital costs, this direct air capture approach could potentially operate at around $200 per ton of CO_2 captured.[31]

Deep Eutectic Solvents (DESs) are increasingly regarded as a new class of ionic liquid analogs due to their shared properties and functional similarities. Bera et al.[32] first synthesized two ionic liquids, i.e., tetraethylammonium Alaninate ([N2222][Ala]) and tetraethylammonium Lysinate ([N2222][Lys]), and then formulated DESs by combining these ionic liquids, acting as hydrogen-bond acceptors, with ethylene glycol as a hydrogen-bond donor. The resulting DESs demonstrated lower viscosity and improved CO_2 absorption performance compared to the original ionic liquids. Vapor–liquid equilibrium testing revealed that the [N2222][Lys]-based DES exhibited significantly greater CO_2 uptake than its [N2222][Ala]-based counterpart. When tested for direct air capture, both DESs efficiently absorbed atmospheric CO_2, with the [N2222][Lys] formulation achieving a maximum uptake of 1.06 mol CO_2 per mol solvent, compared to 0.47 mol/mol for the [N2222][Ala] DES. Furthermore, these DESs maintained their CO_2 capture and release capabilities over multiple absorption–desorption cycles, demonstrating good reversibility and potential for repeated use in carbon capture applications.[32]

Moreover, three DESs, each composed of different ratios of tetrabutylphosphonium bromide and triethylene glycol, were investigated using molecular dynamics simulations and density functional theory calculations.[33] Findings revealed that the bulky phosphonium cations helped organize CO_2 molecules into cage-like arrangements, while the high polarity of triethylene glycol played a dominant role in CO_2 capture efficiency. Among the formulations, the DES with a 1 : 2 molar ratio of tetrabutylphosphonium bromide to triethylene glycol (DES2) exhibited the most favorable structural organization and strongest affinity for CO_2. Further simulations under ambient conditions (400 ppm CO_2) demonstrated DES2's high selectivity for capturing CO_2 over nitrogen and oxygen, indicating strong potential for its use in direct air capture applications.[33]

Khan et al.[34] investigated the use of L-lysine salts, specifically potassium and sodium variants, as environmentally friendly solvents for the direct capture of carbon dioxide from the air. These bio-based solvents are designed to lower the environmental footprint of direct air capture systems by minimizing harmful emissions and supporting more sustainable process development. Laboratory experiments assessed the CO_2 solubility of these salts at 25 °C under different pressures (30-100 kPa) and gas flow rates (10-30 L/min), achieving CO_2 loading capacities up to 1.0 mol CO_2 per mol of solvent. The results demonstrate that L-lysine salt solutions perform on par with conventional direct air capture solvents in terms of CO_2 uptake.[34] Additionally, the chemical properties and molecular stability of L-lysine salts make them strong contenders for green direct air capture technologies, offering a stable and sustainable alternative for atmospheric CO_2 capture.

Potassium glycinate was found to demonstrate similar working capacity and liquid-phase mass transfer efficiency to the widely used industrial solvent monoethanolamine, but significantly surpassed it due to its much lower regeneration temperature.[35] To evaluate the suitability of potassium glycinate for large-scale direct air capture applications, a simulation was conducted, incorporating experimentally determined equilibrium and kinetic parameters, as well as the operational features of a gas-solvent hollow fiber membrane contactor. Results from the full-scale simulation indicate that potassium glycinate, when used in an absorption–desorption cycle ranging from 20 °C to 90 °C, can remove up to 83% of atmospheric CO_2 and achieve 55% regeneration within a single pass through the membrane system. This notably low operating temperature range offers a major advantage over the conventional 40 °C-140 °C thermal swing used in current industrial CO_2 capture processes.[35] As a result, potassium glycinate emerges as a promising and sustainable solvent choice for energy-efficient direct air capture systems, especially when paired with renewable heat sources.

A range of solvent mixtures composed of a reactive ionic liquid, featuring an imidazolium-based cation and a pyrrolide anion, combined with ethylene glycol in various ratios, was examined for capturing carbon dioxide at low partial pressures (significantly below 0.1 bar to up to 1 bar).[36] The system demonstrated the ability to absorb considerable amounts of CO_2, even at concentrations below 5,000 ppm in nitrogen. The study identified three reversible chemical pathways for CO_2 uptake, leading to the formation of carbonate (predominant), carboxylate (intermediate), and carbamate (least abundant) products. Under conditions of 100% relative humidity, bicarbonate species were also observed alongside carbonates. Furthermore, the solvent showed enhanced absorption efficiency and required a lower temperature for mild regeneration compared to amines and ionic liquids that react with CO_2.[36]

Improving the contactor design is another strategy for improving the liquid solvent-based systems.[37] The performance optimization of a laboratory-scale direct air capture system was explored using a crossflow air-liquid contactor equipped with a 3D-printed Gyroid-structured packing and a potassium sarcosinate solvent. Findings indicate that this Gyroid design delivers CO_2 capture efficiency on par with traditional packed bed systems, while reducing pressure drop by as much as 77.8%.[37] This significant decrease in pressure loss highlights the Gyroid structure's promise as a more energy-efficient and economically viable option for gas-liquid contactors in direct air capture applications.

Brethomé et al.[38] presented a laboratory-scale method for direct air capture that primarily utilizes readily accessible, commercially available materials and equipment. In the first step, carbon dioxide was captured using environmentally benign aqueous solutions of amino acids, specifically glycine and sarcosine, delivered through a standard household humidifier. Once CO_2 was absorbed, the solution was treated with a basic guanidine compound, which reacted to form a highly insoluble carbonate salt, simultaneously regenerating the amino acid absorbent. In the final step, concentrated solar energy was used to gently heat the carbonate crystals, efficiently releasing the captured CO_2 and allowing for near-complete recovery of the guanidine reagent.[38] The study highlighted the potential for incorporating renewable energy into direct air capture applications. McQueen et al.[39] also found that geothermal power facilities can generate high-quality, compressed CO_2 at a cost of \$300 per ton or less, with the potential to expand their capacity to handle up to 19 million tons of CO_2 annually.

A screening study evaluated various alkanolamines, especially those used in conventional carbon capture and storage, for their potential in direct air capture.[40] Using 1.5 $mol \cdot dm^{-3}$ aqueous solutions, their CO_2 absorption from compressed air over 24 hours was tested. Results revealed that primary, unhindered amines are particularly effective, matching the efficiency of alkali hydroxides while offering lower energy requirements for regeneration. High CO_2 uptake is strongly linked to the formation of amine carbamates. However, in some strongly basic amines (e.g., 2-(ethylamino)ethanol, 2-(butylamino)ethanol), carbonate/bicarbonate formation also contributed to effective capture. In contrast, amines that do not form carbamates, such as 2-amino-2-methyl-1-propanol, despite their success in carbon capture and storage, performed poorly in direct air capture due to slower reaction kinetics with ultra-dilute CO_2.[40]

Methylglyoxal-Bis(Iminoguanidine) (MGBIG) is a promising material for direct air capture of CO_2 through crystallization of guanidinium carbonate.[41] A study explored how various aqueous amino acids and peptides affect its performance. Most tested amino acids reacted with MGBIG, forming precipitates that hinder CO_2 capture. However, sarcosine, the only one with a secondary amine, remained soluble and significantly boosted performance. Adding just 0.5 mmol of sarcosine to 5 mmol of MGBIG increased CO_2 uptake from 0.7 to 4.15 mmol, demonstrating strong synergy between the two and highlighting their potential for efficient direct air capture.[41] Custelcean et al.[42] presented a bench-scale direct air capture method using aqueous salts of amino acids, specifically potassium glycinate and potassium sarcosinate, for CO_2 absorption. The captured CO_2 was then transferred to solid meta-Benzene-Bis(Iminoguanidine) (m-BBIG), which reacted at room temperature to form a crystalline carbonate salt, $(m\text{-}BBIGH_2)(CO_3)(H_2O)_n$ (where n = 3-4). CO_2 was later released by gently heating the crystals (60-120 °C), fully regenerating the m-BBIG. Unlike conventional processes, this approach avoided heating the amino acid solutions, reducing degradation and extending sorbent lifespan. Over three capture-release cycles, the CO_2 loading capacity of the sarcosine/m-BBIG system ranged from 0.12 to 0.20 mol of CO_2 per mol of sorbent.[42]

Direct air capture of CO_2 is essential for addressing climate change, but its efficiency is hindered by the low atmospheric CO_2 concentration (~400 ppm).[43] To overcome this challenge, a new direct air capture system was developed using lysine as the CO_2 sorbent and nitrogen-doped 3D graphene as a dual-function catalyst that enhances both CO_2 uptake and release.[44] Adding just 500 ppm of nitrogen-doped 3D graphene extended the high-efficiency CO_2 capture time ($\geq 90\%$ efficiency) by 233% and nearly doubled the CO_2 absorption capacity (197% increase). The catalyst also dramatically improved the desorption performance, boosting both capacity and rate by about 280% and 338% at 70 °C, making it possible to regenerate the sorbent using low-grade heat. The system maintained excellent performance over 50 consecutive capture-release cycles, demonstrating strong durability.[44]

3.1.2 *Feasibility and future directions*

Traditional alkaline and amine-based systems, while mature, are constrained by high energy demands, solvent degradation, and environmental risks. To overcome these limitations, a shift toward bio-derived, low-volatility, and thermally stable alternatives, such as ionic liquids, DESs, and amino acid-based solvents, is gaining momentum.

These novel solvents demonstrate impressive CO_2 uptake capacities, improved regeneration profiles, and reduced environmental footprints. For instance, potassium glycinate and lysine salts not only rival the performance of monoethanolamine but also require significantly lower regeneration temperatures, enhancing energy efficiency.[35,44] Similarly, advances in combining bio-waste-derived amino acids with guanidine crystallization or graphene-based catalysts point to integrated systems that achieve high capture rates with minimal thermal input, ideal for coupling with renewable energy sources.[34] These findings suggest that tailored molecular design, synergistic sorbent-catalyst pairings, and modular regeneration strategies can unlock scalable, low-cost direct air capture systems.

Additionally, optimizing reactor and contactor configurations is emerging as a key strategy for translating solvent advancements into viable direct air capture systems. Research into novel geometries, such as 3D-printed Gyroid-structured packings, demonstrates potential for lowering pressure drops and enhancing gas–liquid contact efficiency, thereby reducing system-level energy penalties.[37] Furthermore, coupling these innovations with robust solvent systems, like DESs with tunable viscosity and cyclic stability, could dramatically improve long-term operability and reduce lifecycle costs.[32,33,36] Future efforts should focus on techno-economic assessments, real-world pilot testing under varying climatic conditions, and integration with renewable energy and waste heat sources. Computational modeling and simulation, such as Aspen Custom Modeler® analyses, should guide solvent and process selection to balance kinetics, thermodynamics, and infrastructure needs.[35] Table 1 below summarizes the feasibility of various liquid solvent-based direct air capture systems.

Table 1. Comparison of liquid solvent-based direct air capture systems

Solvent/system	CO_2 uptake capacity	Regeneration energy	Stability and scalability	Cost/feasibility notes	Ref.
KOH/NaOH aqueous solutions	High (low ppm air)	High (calcination needed)	High stability, slow kinetics	High capital and operating costs	24
Amine-based solvents	High (carbamate/ bicarbonate formation)	High (> 3 GJ/ton)	Degrade under O_2/heat	Health/environmental concerns, costly	40
Ionic liquids ([P66614][Im])	0.3-0.6 mol/kg	15.15-35.42 MJ/kg	High stability, customizable	Approx. $200/ton possible	29
Bio-derived ionic liquids	1 CO_2 : 2 ionic liquid (good at low concentrations)	Mild, reversible	Bio-derived, low toxicity	Utilize waste amino acids	30
Deep eutectic solvents ([N2222][Lys] + ethylene glycol)	Up to 1.06 mol/mol	Low, repeatable cycles	Good reversibility, scalable	Lower viscosity, tunable	32
L-lysine salts	Up to 1.0 mol/mol	Low (sustainable regeneration)	Environmentally friendly	Green, promising	34
Potassium glycinate	83% removal in simulation	20-90 °C (low-grade heat)	Durable, efficient	Energy-efficient, scalable	35
Imidazolium-pyrrolide ionic liquid + ethylene glycol	Effective at < 5,000 ppm	Lower than amines/ionic liquids	Customizable, structurally strong	Selective, low temperature	36
Potassium sarcosinate with 3D Gyroid contactor	Comparable to packed bed systems	Reduced pressure drop improves energy feasibility	Scalable with improved design	Energy-saving contactor	37
Glycine/sarcosine + guanidine + solar regeneration	Efficient absorption, solar regeneration	Low (solar heating)	Renewable integration possible	Simple equipment, low cost	38
Unhindered primary alkanolamines	Effective if forming carbamates	Lower than alkali, varies by amine	Dependent on amine structure	Screened for direct air capture suitability	40
Sarcosine + m-BBIG crystallization	0.12-0.20 mol/mol	60-120 °C (gentle heating)	Stable over 3 cycles	Avoids amino acid heating	41, 42
Lysine + N-doped 3D graphene catalyst	197% increase in capacity versus base system	Low (efficient with low-grade heat)	Durable (more than 50 cycles)	High capacity, efficient cycles	44

As indicated in Table 1, while the novel solvent-based systems for direct air capture offer advantages such as low volatility, high CO_2 selectivity, and lower regeneration temperatures, they face several limitations that hinder commercial scalability. These include high viscosity (as for ionic liquids which reduce mass transfer), complex synthesis or high material costs, limited long-term stability, and uncertain environmental impacts. Additionally, some systems exhibit slower kinetics or lower capture capacities under ambient conditions (e.g., 2-amino-2-methyl-1-propanol, [N2222][Ala]-based DES and reactive ionic liquid systems at low CO_2 partial pressure).[29,33,37] To overcome these challenges, it is also crucial to optimize solvent formulations for improved CO_2 loading and faster kinetics, incorporate renewable or waste-derived components to enhance sustainability, and develop energy-efficient regeneration strategies such as low-grade heat utilization or catalytic desorption. Overall, the feasibility of liquid solvent-based direct air capture is improving rapidly, provided research continues to integrate green chemistry, materials innovation, and process intensification.

3.2 *Solid sorbent-based systems*

3.2.1 *Advances*

Solid sorbent-based systems represent a rapidly advancing and energy-efficient approach for direct air capture of carbon dioxide from the atmosphere. These systems typically utilize porous materials, such as amine-functionalized silica, MOFs, zeolites, or resins, that selectively adsorb CO_2 through physisorption or chemisorption at low partial pressures (~400 ppm) (Figure 2).[45] Examples of chemical reactions (chemisorption and regeneration) using amine-functionalized silica are shown below:

Dry conditions (formation of carbamate): $2RNH_2 + CO_2 \leftrightarrow RNHCOO^- + RNH_3^+$, where RNH_2 is a primary amine on the silica surface. The reaction is reversible, with the reverse reaction regenerating CO_2.

$$\text{Humid conditions (formation of bicarbonate): } RNH_2 + CO_2 + H_2O \rightarrow RNH_3^+ + HCO_3^-$$

$$\text{Regeneration (for bicarbonate): } HCO_3^- + \text{heat} \rightarrow CO_2 + OH^-$$

As for physisorption, zeolites, for instance, with high surface areas and polar frameworks, adsorb CO_2 via weak electrostatic interactions as shown below:

$$\text{Zeolite} + CO_2\,(g) \leftrightarrow \text{Zeolite}\cdot CO_2$$

A key advantage of solid sorbents lies in their lower regeneration temperatures (often between 80-120 °C) compared to liquid solvent systems, enabling integration with low-grade or renewable heat sources (Figure 2). Moreover, the modular and scalable design of solid sorbent units makes them attractive for distributed carbon removal applications. However, current limitations persist, including slow CO_2 uptake kinetics, performance degradation over multiple cycles due to moisture sensitivity or oxidative damage, and reduced adsorption capacity in the presence of humidity–an inherent challenge in ambient air capture. In addition, many advanced sorbents remain expensive or difficult to synthesize at scale.[46] Recent research in this domain aims to address these limitations.

By evaluating five different porous adsorbents for direct air capture, Wu et al.[47] found that LiX (a physisorbent derived from zeolite 13X and Li) offered fast adsorption, low cost, low heat of adsorption, and good stability, but suffered from very low capacity and poor performance in humid conditions. Polyethyleneimine (PEI)-coated resin HP20 showed high CO_2 capacity and affordability, and worked well in humidity, but had slow adsorption rates and limited stability. TRI-PE-MCM-41 (made by attaching (3-[2-(2-aminoethylamino)ethylamino]propyltrimethoxysilane) to mesoporous silica MCM-41) provided moderate capacity, fast kinetics, and excellent stability, though it had a high heat of adsorption and cost. mmen-Mg_2(dobpdc) (a unique amine-functionalized MOF), where mmen (N,N'-dimethylethylenediamine) binds to open metal sites on Mg_2(dobpdc) delivered high capacity and stability with moderate kinetics and heat, but was expensive. Lewatit (a commercial direct air capture sorbent, which is a highly hydrophilic ion-exchange resin with primary benzyl amine groups) offered balanced performance at low cost, with modest capacity and kinetics, but its CO_2 uptake improved significantly in humid environments.[47] These findings suggest that adsorbent selection should be tailored to specific application needs to optimize direct air capture performance.

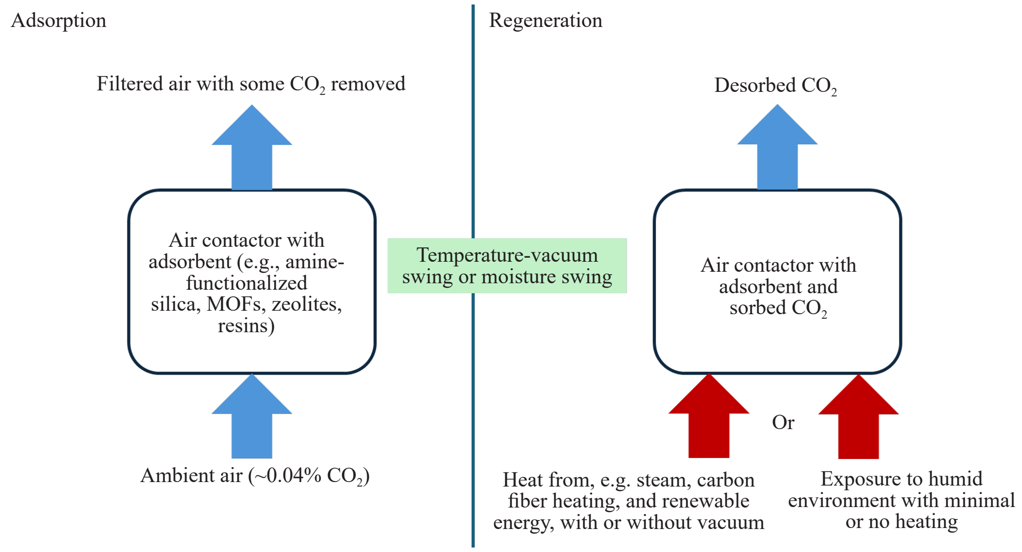

Figure 2. Solid sorbent-based system for direct air capture of carbon dioxide

Wiegner et al.[48] studied how changes in ambient conditions affect the performance of sorbent-based direct air capture systems and explored optimal design and operation strategies. They developed a new modeling approach that connects thermodynamic simulations of adsorption with mixed-integer linear optimization through a simplified direct air capture model. The system employs a vacuum-temperature swing cycle modeled under various environmental conditions using a representative amine-based sorbent. They analyzed optimal setups for (1) stand-alone direct air capture plants at three locations and (2) direct air capture integrated into renewable-powered energy hubs. Results show that allowing the system to adapt to weather conditions and operate flexibly, such as by CO_2 storage, yields better performance. While simpler operation strategies are less efficient, they require less complex control. Notably, capture costs are lower in cold, humid climates for both stand-alone and integrated systems.[48]

The performance of three amine-based chemisorbents and two physisorbents was assessed for direct air capture using Temperature-Vacuum Swing Adsorption (TVSA) and steam-assisted TVSA (s-TVSA) (Figure 2).[49] Process optimization highlighted trade-offs between energy use and productivity. Most energy demand stemmed from CO_2 and steam desorption, as well as heating the sorbent material. Although steam purging typically increased energy use, it sometimes improved both productivity and efficiency. The best-performing sorbents showed energy use ranging from 6.25 to 30.4 GJ per ton of CO_2 and productivity between 0.01 and 0.15 tons of CO_2 per day per ton of sorbent. All sorbents could meet the 95% CO_2 purity target using moderate vacuum levels (around 0.3 bar), while deeper vacuums (0.05 bar) further reduced energy needs and boosted performance. Additionally, a new ambient-pressure thermal swing cycle was proposed, achieving the desired purity but with higher energy requirements than vacuum-based approaches.[49]

To assess the scalability of s-TVSA, a study introduced an advanced simulation tool for purifying CO_2 from air using a five-step s-TVSA.[50] Using (3-aminopropyl)diethoxymethylsilane-modified nanofibrillated cellulose as a reference adsorbent, the system was optimized for both energy efficiency and productivity while maintaining high CO_2 purity. In the reference scenario, maximum productivity and minimum specific work were calculated, aligning reasonably with existing data. The results highlight that formal optimization methods outperformed heuristic designs in identifying performance limits. Optimal productivity was achieved with moderate sorption kinetics and compact contactor designs. Additionally, moderate to high humidity (50-75%) enhanced performance, and the system remained effective across a wide ambient temperature range (5-30 °C) when optimized.[50]

Abdelnaby et al.[51] introduced a modification approach for the MOF UiO-66 to enhance its ability to capture carbon dioxide from air at trace (ppm) concentrations. The hydroxyl-functionalized version of UiO-66 (UiO-66-$(OH)_2$) was chemically modified using (3-aminopropyl)triethoxysilane (APTES) to produce UiO-66-APTES, incorporating multiple aliphatic amine groups. This modification significantly boosted CO_2 adsorption capacity at 298 K and 1 bar, from 42.7 cm^3/g to 65.6 cm^3/g, marking about a 150% increase compared to the unmodified material. The functionalized

MOF also demonstrated strong CO_2 selectivity over N_2, with a high selectivity factor of 160, and maintained stable performance over 15 adsorption-desorption cycles.[51] Additionally, dynamic tests confirmed the material's effectiveness in separating CO_2 from air, highlighting its potential as a promising sorbent for direct air capture applications.

Moisture-swing adsorption is a promising direct air capture method due to its low regeneration cost and operational simplicity, especially with amine-based Anion-Exchange Resins (AERs) (Figure 2). However, current AERs face challenges like limited CO_2 capacity and poor desorption efficiency.[52] Wang et al.[53] introduced a new sorbent, Diamine-Double Quaternary (DQ)-AER, a diamine-modified double quaternary ammonium resin, created by modifying commercial resins with tertiary diamines. Compared to Single Quaternary-AER (Diamine-SQ-AER), the new material has a much higher quaternary ammonium content (68-81%) and achieves a record CO_2 uptake of 3.41 mmol/g under direct air capture conditions, nearly twice that of Diamine-SQ-AER. It also maintained stable performance over six cycles, surpassing most existing moisture-swing direct air capture sorbents.[53]

Solid amine sorbents offer good CO_2 uptake and kinetics, but their powdered form leads to high pressure drops in packed-bed systems, limiting large-scale use.[54] To overcome this, Min et al.[55] presented a new type of laminate-supported CO_2 sorbent, made by embedding branched PEI into expanded Polytetrafluoroethylene (PTFE) sheets with silica particles. These free-standing sheets, created via a scalable wet impregnation process, maintained porosity and enabled CO_2 capture capacities of 0.4-1.6 mmol/g under dry conditions. The material performed well in both dry and humid temperature swing cycles, showing good stability. Importantly, regeneration required only 287 kJ/mol CO_2, with a water-to-CO_2 ratio of 3.1, the lowest reported among direct air capture sorbents using hydrophobic materials, highlighting its efficiency and practical potential.[55]

Many amine-impregnated porous sorbents have been developed for direct air capture, but how the amine interacts with the support material remains poorly understood. Rim et al.[56] compared Tetraethylenepentamine (TEPA) on two supports, namely γ-Al_2O_3 and MIL-101(Cr), under varying temperatures (-20 to 25 °C) and humidity (0-70% relative humidity). CO_2 adsorption mechanisms differed with weak chemisorption (carbamic acid formation) dominated on MIL-101(Cr), while strong chemisorption (carbamate formation) occurred on γ-Al_2O_3. Humidity enhanced both mechanisms, especially at -20 °C. Despite high water uptake at low temperatures, its impact on cyclic direct air capture performance was limited due to slow water adsorption.[56] The findings show that CO_2 capture behavior can be tuned by modifying amine-support interactions, and that water uptake depends heavily on the support's properties. Along the same vein, Priyadarshini et al.[57] evaluated CO_2 adsorption of amine-loaded porous alumina using PEI and TEPA under dry and humid conditions at 25 °C and -20 °C. At 25 °C and 400 ppm CO_2, the highest uptake (1.8 mmol/g) was achieved by γ-Al_2O_3 with 40 wt% TEPA, while 40 wt% PEI showed moderate capacity (0.9 mmol/g). Lower amine content and colder temperatures reduced overall capacity. Under dry conditions at -20 °C, 40 wt% and 20 wt% TEPA samples performed best, with uptakes of 1.6 and 1.1 mmol/g, respectively, and maintained stable working capacities across 10 cycles. Moisture (70% relative humidity) further enhanced CO_2 adsorption at both temperatures.[57] Overall, PEI- and TEPA-impregnated γ-Al_2O_3 show strong potential for direct air capture in both ambient and cold environments.

Electrically driven Temperature Swing Adsorption (ETSA) is a promising method for direct air capture due to its simplicity and compatibility with renewable electricity.[58] Lee et al.[59] performed a roll-to-roll fabrication of sorbent-coated carbon fibers that can capture about 1.2 mmol CO_2 per gram of fiber at 400 ppm CO_2. When a voltage was applied, the fibers heated up rapidly through Joule heating, reaching regeneration temperatures in under a minute. Compared to conventional heating, this method releases CO_2 six times faster. The system's modular design and fast cycling made it highly suitable for scalable direct air capture applications. A pilot-scale techno-economic analysis estimated a cost of $160 per ton of CO_2, with only 7% of the Joule heating lost to ambient convection during desorption.[59]

Rim et al.[60] developed hybrid CO_2 capture materials called Solvent-Impregnated Polymers (SIPs) to improve the CO_2 absorption performance of thick, water-lean solvents. These materials embedded liquid-like Nanoparticle Organic Hybrid Materials functionalized with Ionized Polyethylenimine (NOHM-I-PEI (NPEI)) into a Ultraviolet (UV)-cured, gas-permeable shell, creating solid sorbents (NPEI-SIPs) with uniform NOHMs distribution. This structure boosted the contact area between NOHMs and CO_2, enhancing capture rates by up to 50 times compared to the unmodified liquid material. Optimal performance was observed at around 49% NOHM loading and 50 °C. NPEI-SIPs maintained stability over 20 thermal cycles and achieved CO_2 loadings of 3.1 mmol/g for post-combustion conditions (15% CO_2) and 1.7 mmol/g for ambient air (400 ppm).[60] This highlights their potential for both direct air capture and flue gas treatment, combining the advantages of both liquid solvents and solid sorbents.

Sujan et al.[61] tested the use of polymer/silica fiber sorbents enhanced with PEI for direct air capture of CO_2. The monolithic fibers, made from cellulose acetate and silica (SiO_2), were produced using a dry-jet, wet-quench spinning method. After fabrication, the fibers were infused with low-molecular-weight PEI (800 Da) through a straightforward and scalable process. These sorbents were evaluated under both near-equilibrium and breakthrough conditions for CO_2 capture. Notably, their CO_2 capacity remained nearly unchanged under dry conditions even after several humid breakthrough cycles. The system was also able to deliver high-purity CO_2 using a combined vacuum and thermal desorption process, with or without moisture present. When tested with dry air containing 380 ppm CO_2, the setup achieved a peak CO_2 purity of 98%.[61]

3.2.2 *Feasibility and future directions*

Solid sorbent-based systems have emerged as a leading technology for direct air capture due to their energy efficiency, scalability, and adaptability to varying environmental conditions. These systems, using materials such as amine-functionalized silica, zeolites, MOFs, and resins, can selectively capture CO_2 at ambient concentrations through physisorption or chemisorption. Unlike liquid solvent systems, they operate at relatively low regeneration temperatures (80-120 °C), making them compatible with renewable heat sources. Modular unit designs also enable deployment across diverse locations, including integration with renewable energy hubs.[62] However, key challenges remain: adsorption performance varies with humidity levels across different sorbents (some, such as TEPA on γ-Al_2O_3 or MIL-101(Cr) and amine-based sorbents, perform better at higher humidity while others, like LiX, show reduced performance under similar conditions), slow kinetics, sorbent degradation over cycles, and high costs of advanced materials. Research into novel sorbents, such as amine-loaded MOFs (e.g., mmen-Mg_2(dobpdc)), PEI-coated resins, and modified UiO-66 frameworks, has shown promise in enhancing CO_2 uptake, stability, and selectivity.[47,49,51] Advances in sorbent architecture, such as laminate-supported systems and hybrid polymer matrices, have further improved stability and regeneration efficiency, paving the way for more practical and cost-effective direct air capture deployment.

Future research in sorbent-based direct air capture is moving toward optimizing materials and process integration for real-world conditions. Modeling and simulation studies have revealed that tailoring system operation to ambient climate, such as through TVSA or steam-assisted TVSA, can significantly improve efficiency and reduce capture costs, especially in cool, humid environments. ETSA also offers rapid regeneration and modularity, with promising cost estimates under $200/ton CO_2. Meanwhile, next-generation materials like moisture-swing amine-exchange resins (e.g., Diamine-DQ-AER) and surface-functionalized fibers show that sorbent design can balance capacity, kinetics, and stability across humidity levels. Additionally, a deeper understanding of amine–support interactions is crucial to improving performance under fluctuating temperatures and moisture levels. As techno-economic analysis, material science, and process engineering converge, the focus will shift from laboratory breakthroughs to system-level optimization, scale-up, and long-term operational reliability. These are essential for making direct air capture a viable tool for large-scale carbon dioxide removal. Table 2 below summarizes the feasibility of various solid sorbent-based direct air capture systems.

Table 2. Comparison of solid sorbent-based direct air capture systems

Sorbent/system	CO_2 uptake capacity* (mmol/g)	Regeneration energy	Stability and scalability	Limitations	Ref.
LiX (zeolite-based)	Low (~0.17-0.21)	Moderate	Good stability; low-cost; scalable	Very low capacity; poor humidity tolerance	47
HP20 resin	High (~0.48-2.21)	High	Affordable; moderate durability	Slow kinetics; limited long-term stability	47
TRI-PE-MCM-41 (silica-amine)	Moderate (~0.59-0.81)	High	Excellent stability; limited scalability	Expensive; high regeneration energy	47

Table 2. (cont.)

Sorbent/system	CO_2 uptake capacity* (mmol/g)	Regeneration energy	Stability and scalability	Limitations	Ref.
mmen-Mg_2(dobpdc) (MOF)	High (~0.18-2.25)	Moderate	Excellent stability; hard to scale	High cost; moderate kinetics	47
Lewatit (commercial resin)	Moderate (~0.52-0.90)	Moderate	Durable; cost-effective; commercial	Modest capacity and kinetics	47
UiO-66-APTES (modified MOF)	High (~1.6-2.65)	Low	Durable over 15 cycles; lab-scale	Synthesis complexity; not yet scaled	51
Diamine-DQ-AER (moisture-swing)	Very High (~3.41)	Low	Excellent performance; good for humid direct air capture	Limited desorption efficiency	53
Laminate-supported PEI/PTFE	Moderate (~0.4-1.6)	High	High stability; scalable wet processing	Requires novel infrastructure	55
PEI/TEPA on γ-Al_2O_3	High (~0.9-2.0)	Moderate to high	Strong cyclic stability; humidity resilient	Lower amine = reduced capacity	56, 57
Electrically driven (ETSA)	High (~0.4-1.9)	Very high	Fast cycling; scalable	Early-stage; integration challenges	58
Solvent-Impregnated Polymers (SIPs)	High (~1.7-3.1)	Moderate	Stable; scalable; hybrid design	Fabrication complexity; need validation	60
PEI-enhanced polymer/silica fibers	Moderate (~0.59-1.6)	Moderate to high	Good stability; scalable	Early-phase; need broader validation	61

*CO_2 uptake capacity varies with temperature and pressure. The values shown indicate the highest and lowest measurements under different experimental conditions or the mean measurements associated with a particular experimental condition

3.3 *Electrochemical direct air capture*

3.3.1 *Advances*

Electrochemical direct air capture of carbon dioxide is an emerging technology that leverages electrical energy to selectively capture and release CO_2 from ambient air using redox-active materials or ion-exchange membranes (Figure 3).[63] Unlike traditional solid sorbent-based systems, which rely on materials such as amine-functionalized solids that physically or chemically bind CO_2 and require thermal regeneration, electrochemical direct air capture enables regeneration at lower temperatures and with potentially greater energy efficiency by using applied voltage to drive reversible CO_2 binding reactions (Figure 3).[64] Similarly, in contrast to liquid solvent-based systems, such as aqueous amine solutions that absorb CO_2 and require significant heat input for desorption, electrochemical direct air capture avoids the need for bulky thermal equipment and can operate with intermittent renewable electricity, offering modularity and a smaller carbon footprint.[65] This approach represents a promising pathway for scalable, energy-efficient carbon removal directly from the atmosphere.

Traditional methods for capturing carbon dioxide from ambient air typically demand between 230 and 800 kJ of thermal energy per mole of CO_2, making energy consumption the primary cost driver. In contrast, Seo and Hatton[66] introduced an electrochemical direct air capture approach that used neutral red as a redox-active compound in water, with nicotinamide added to improve its solubility as a hydrotropic agent. In a continuous flow electrochemical cell, the system achieved efficient electron use, reaching a utilization rate of 0.71 when processing a gas stream containing 15% CO_2, with a calculated minimum energy requirement of just 35 kJ of electrical energy per mole of CO_2. When applied to ambient air conditions containing 410 ppm CO_2 and 20% oxygen, the setup maintained functionality with an electron utilization of 0.38 and an estimated minimum energy input of 65 kJ per mole of CO_2.[66] Additionally, Seo et al.[67] presented a durable electrochemical system based on a redox-active amine that achieved high electron efficiency, capturing up to 1.25 moles of CO_2 per mole of electrons by binding two CO_2 molecules per amine molecule in aqueous solution, with an energy cost of 101 kJ per mole of CO_2. When capturing CO_2 directly from ambient air, the system maintained an electron utilization efficiency of 0.78. The 1-Aminopyridinium (1-APyl) radical solution consistently captured CO_2 across a wide range of inlet concentrations, from as low as 1% up to 100%. The system's performance remained stable over at least five cycles, showing no notable degradation, and the 1-APyl radical also exhibited good resistance to oxidation by O_2, making it promising for use in direct air capture scenarios. Beyond direct air capture, this redox cycle based on the 1-AP cation offers potential for large-scale CO_2 separation processes without requiring heat-driven regeneration of amine solutions.[67] Unlike other electrochemical regeneration strategies that rely on proton or metal ion release from an anode to shift CO_2 binding equilibria, this approach uses a direct redox mechanism that allows for continuous and stable functioning.

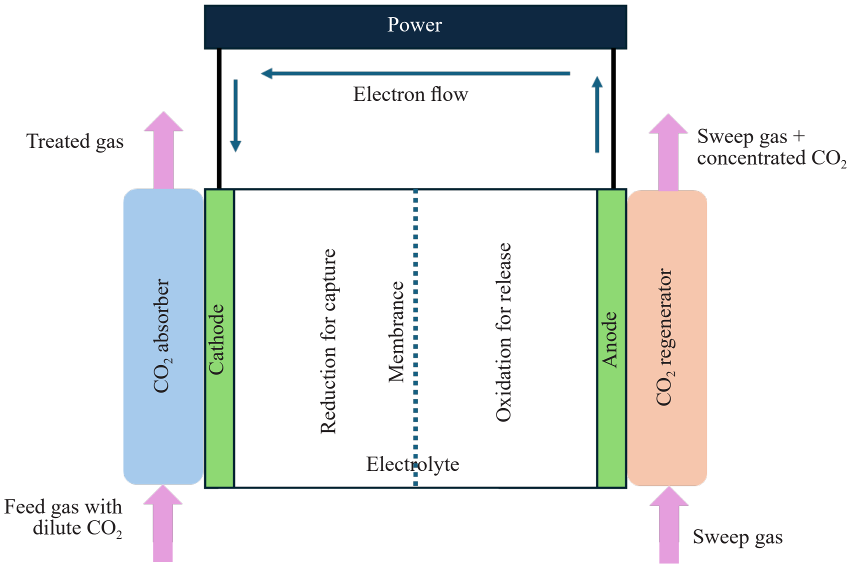

Figure 3. Schematics of electrochemical direct air capture

Many organic compounds currently investigated for electrochemical CO_2 capture degrade over time when subjected to repeated redox cycles, especially in oxygen-rich environments, leading to unwanted chemical byproducts.[68] Additionally, commercially available electrochemical flow cells, essential components for redox-based systems, are prohibitively expensive, often costing thousands of dollars each.[65] To overcome these limitations, a study evaluated the durability of five organic molecules, namely pyrazine, 4,4’-bipyridine, phenazine, 1,4-benzoquinone, and 2,3,5,6-tetrachloro-p-benzoquinone, for their potential in direct air capture.[69] Phenazine emerged as the most effective candidate, maintaining a consistent coulombic efficiency of 100% during 9.5 hours of operation, with a theoretical minimum energy input of 77.2 kJ per mole of CO_2 captured. A cost-effective, 3D-printed redox flow cell designed specifically for electrochemical direct air capture applications was introduced. This customizable cell significantly reduced internal resistance and accommodated various electrode sizes. Unlike traditional multi-chamber cells, which are expensive and hinder scalability, the 3D-printed alternative costs under $4, offering a promising low-cost solution for the broader adoption of redox flow technologies.[69]

In a separate study, Wenger and D’Alessandro[70] presented an environmentally friendly, water-based electrochemical direct air capture system that used Alizarin Red S as the redox-active CO_2 capture agent. The system operated with a low theoretical minimum energy demand of 24.6 kJ of electrical energy per mole of CO_2 and demonstrated excellent long-term performance, completing over 100 cycles across 205 hours with a consistent coulombic efficiency of 100% and an average capacity retention of 99.8%. A techno-economic assessment further examined how factors such as current density and electrode surface area influenced the overall cost, outlining strategies to reduce the levelized cost of carbon capture to below US$500 per metric ton of CO_2.[70]

Murase et al.[71] established a reliable electrochemical system for repeated CO_2 capture and release using a trinuclear zinc(II) complex (Zn_3L) as the active CO_2-binding agent, with an ionic liquid serving as the supporting electrolyte to ensure operational stability. The system achieved a more rapid CO_2 fixation rate compared to an alkaline solution of equivalent concentration. The capture-release mechanism relied on the reversible breakdown and reformation of the zinc complex, triggered by protons (H^+) and hydroxide ions (OH^-) generated through a bipolar membrane integrated into the electrochemical cell. Notably, the process remained effective even under low CO_2 concentrations typical of ambient air (450 ppm), capturing around 46% of the CO_2 present in an airstream flowing at 200 mL per minute.[71] Chae et al.[72] explored the use of an electrochemical cell equipped with an Anion-Exchange Membrane (AEM) for carbon dioxide separation in direct air capture systems. The cell operates by transporting anions such as OH^-, CO_3^{2-}, and HCO_3^- through the AEM, with the overall mechanism depending on the dominant ion species involved. The optimized system achieved a CO_2 capture efficiency of 95.7% from air containing 400 ppm CO_2, demonstrating its strong potential for direct air capture applications.[72]

Li et al.[73] introduced an innovative solid electrolyte reactor featuring a highly conductive cathode designed for the simultaneous direct air capture of CO_2 and H_2O. The system includes a polypropylene polyelectrolyte layer infused with Polyethylene Oxide (PEO) and potassium hydroxide (KOH), as well as a nickel-based anode also filled with PEO/KOH. Operating with an energy efficiency of 80%, the reactor continuously produces ethylene and oxygen. The direct air capture utilizes a sorbent made from PEI combined with zeolite 13X for CO_2 capture, and calcium chloride for water absorption. Both materials are embedded within conductive carbon foam structures. Single-Walled Carbon Nanotubes (SWCNTs) serve a multifunctional role by supporting the CO_2 and H_2O sorbents, conducting electrons, and acting as active cathodes that deliver electrons to PEI-bound CO_2, facilitating its reduction to carbon monoxide (CO).[73] The interaction between PEI and SWCNTs is crucial, as it stabilizes the CO_2 radical anion ($CO_2{\bullet}^-$) and concentrates CO_2 at the catalytic surface for enhanced electrochemical conversion. Catalysis for ethylene formation is achieved using copper and copper oxide species generated from copper formate and deposited on the nanotubes. These catalysts drive the coupling of CO intermediates to form ethylene and hydroxide ions (OH^-), consuming eight electrons and eight protons in the process. The resulting OH^- ions are transported through the PEO/KOH-filled polypropylene electrolyte into the nickel anode, where they are oxidized to regenerate water and release oxygen.[73]

Hemmatifar et al.[74] presented a direct air capture system driven by electrochemical processes, utilizing the strong affinity between redox-active quinone groups and CO_2 molecules. Unlike traditional chemisorption methods that depend on thermal or pH changes to trigger CO_2 absorption and release, this system operates purely through applied electrical voltage. In particular, the system uses a Poly(Vinylanthraquinone) (PVAQ) cathode that undergoes a reversible two-electron reduction, allowing it to bind CO_2 from the incoming gas stream. When the PVAQ is subsequently oxidized, it releases the captured CO_2. Both small-scale and intermediate-scale versions of the system were tested using feed gases containing as little as 400 ppm CO_2 (0.04%), with energy requirements as low as 113 kJ per mole of CO_2 captured.[74] A key advantage of this system is its modular bipolar cell architecture, which makes it easily scalable for applications ranging from compact units to full-scale industrial installations.

Zhu et al.[75] designed a continuous electrochemical CO_2 capture system that integrated the O_2/H_2O redox couple with a modular solid-electrolyte reactor. The device performed oxygen reduction and evolution reactions to convert low-concentration CO_2 into carbonate at a high-alkaline cathode–membrane interface. Protons from the anode then neutralized the carbonate, releasing high-purity CO_2 (> 99%) from the central electrolyte layer. This process operated without added chemicals or byproducts. The system achieved high capture rates (up to 86.7 kg CO_2 per day per m^2), Faradaic efficiencies over 90%, carbon removal exceeding 98% from simulated flue gas, and energy use as low as 150 kJ per mole of CO_2, highlighting its strong potential for real-world deployment.[75]

Apart from direct air capture, electrochemical methods are also commonly used to regenerate CO_2 captured from sorbent-based, solvent-based, or electrochemical capture systems. For instance, Bui et al.[76] developed a one-dimensional model, supported by experimental data, that describes the electrochemical release of CO_2 from bicarbonate-rich capture solutions and seawater using bipolar membrane electrodialysis. In the context of direct air capture, both simulations and experiments showed that water dissociation within the bipolar membrane generated pH gradients, which promoted CO_2 liberation at the interface between the cation-exchange layer and the catholyte. This process operates with energy demands below 150 kJ per mole of CO_2. Since this review focuses on direct air capture, the technologies for CO_2 separation after capture are beyond its scope and will not be further covered here.

3.3.2 *Feasibility and future directions*

Electrochemical direct air capture has emerged as a highly promising alternative to conventional thermal-based carbon capture technologies due to its modularity, low-temperature operation, and compatibility with intermittent renewable electricity. Unlike amine-based systems that require significant thermal input, electrochemical direct air capture relies on applied voltage to reversibly bind and release CO_2 through redox-active molecules or ion-exchange membranes. Recent developments, such as those by Seo and Hatton,[66] have demonstrated energy requirements as low as 35-65 kJ/mol CO_2 and stable operation under ambient air conditions. Other approaches using redox-active amines, quinones, or metal-organic complexes have shown similarly high electron efficiencies and durability over multiple cycles.[22,67,74] Furthermore, advancements in low-cost, customizable flow cells and solid-electrolyte reactors, with some achieving over 90% Faradaic efficiency and CO_2 purities above 99%, underscore the scalability and real-world potential of electrochemical systems for atmospheric carbon removal.[73,75]

Despite these encouraging advancements, key challenges remain before electrochemical direct air capture can be widely adopted. Many redox-active compounds suffer from degradation under repeated cycling or in oxygen-rich environments, leading to performance loss and undesired byproducts. High costs of commercial electrochemical cells also hinder scalability, although recent innovations in low-cost 3D-printed cells have begun to address this. Future research should prioritize the development of more robust, oxygen-tolerant redox materials, as well as optimized reactor designs that reduce energy consumption and material costs. Additionally, system integration with renewable energy sources and techno-economic assessments are essential to bring levelized capture costs below US$500 per ton CO_2. With continued innovation, electrochemical direct air capture could play a central role in decentralized, efficient, and sustainable carbon removal strategies.

3.4 *Other direct air capture methods*

3.4.1 *Advances*

Other emerging direct air capture methods include cryogenic direct air capture, biological direct air capture, mineralization-based direct air capture, and photocatalytic direct air capture. Although the first two are direct capture techniques, the latter involve innovative approaches to treating CO_2 captured through conventional direct air capture methods. Cryogenic direct air capture removes CO_2 from ambient air by cooling it until CO_2 condenses or freezes out. This approach exploits the relatively high freezing point of CO_2 (-78 °C), compared to N_2 and O_2 (-210 to -196 °C). This method typically involves bringing the air down to tens of kelvins, capturing the solidified CO_2, and then reheating or decompressing to release it in purified form.[77] Although the concept dates back to early cryogenic air separation processes, only recently has it been proposed explicitly for direct air capture deployment in cold climates or by harnessing low-temperature waste streams.[78] For instance, Kim et al.[79] showcased a near-cryogenic direct air capture system operating at around -78 °C (195 K), using low-cost porous sorbents such as Zeolite 13X and the metal–organic framework CALF-20. The study integrated this capture stage with liquefied natural gas regasification plants, which provided abundant cold energy, dramatically reducing both energy requirements and capital costs. Breakthrough adsorption experiments at 195 K revealed CO_2 capacities between 4.5 and 5.5 mmol/g, with the estimated levelized cost of capture dropping to approximately US$68/ton CO_2, a threefold cost reduction compared to conventional direct air capture methods.[79]

Biological and bio-hybrid direct air capture harnesses living organisms, such as bacteria, algae, and fungi, or engineered microbial systems embedded in solid scaffolds to capture atmospheric CO_2 via natural metabolic pathways. Unlike chemical sorbents, these systems sequester carbon through photosynthesis or biomineralization, storing it in organic biomass and often simultaneously in mineral forms.[80] Dranseike et al.[81] developed a photosynthetically active living material capable of capturing CO_2 through two mechanisms: the generation of microbial biomass and the formation of stable, insoluble carbonates via microbially induced carbonate precipitation. This was accomplished by embedding photosynthetic microorganisms within a printable, polymer-based matrix. The digitally designed and fabricated structures were optimized to provide adequate light exposure and nutrient delivery to the cyanobacteria inside, supporting their sustained activity for over a year. Experimental results show that these living materials could absorb approximately 2.2 ± 0.9 mg of CO_2 per gram of hydrogel over a 30-day period, and 26 ± 7 mg over a span of 400 days.[81] These outcomes demonstrate the promise of photosynthetic living materials as a scalable, low-maintenance approach to CO_2 capture, with potential applications in sustainable construction and climate mitigation.

Photocatalytic direct air capture combines CO_2 capture and its solar-driven conversion into valuable products, such as fuels, using light-activated catalysts. Typically, air is first passed through a solid sorbent (often amine-functionalized) to capture CO_2; then, instead of thermal desorption, concentrated light is used to both release and convert the CO_2 in a downstream photocatalytic reactor.[82] This process creates syngas (a mix of CO and H_2) in a single, integrated system, operating under ambient-temperature, atmospheric-pressure conditions with only sunlight as the energy source. It bypasses the need for high-temperature, high-energy inputs, and simultaneously produces feedstock for further chemical synthesis.[83] Kar et al.[84] developed a gas-phase, two-stage flow reactor designed for direct air capture and on-site utilization of CO_2 to generate syngas (a mixture of CO and H_2) using light, without the need for elevated temperatures or pressures. The system features one bed containing a silica-supported amine adsorbent that extracts CO_2 from ambient air, effectively purifying the outgoing airflow. The captured CO_2 is then released and transformed into syngas using concentrated light in a second bed packed with a photocatalyst composed of silica/alumina, titania, and a cobalt bis(terpyridine) complex. As part of the process, oxidizing products derived from depolymerized polyethylene terephthalate plastics serve as electron donors. The setup is intended to operate on a day-night cycle, capturing CO_2 during the night and converting it into syngas under solar illumination during the day.[84]

Mineralization-based direct air capture focuses on converting CO_2 into stable carbonate minerals, permanently locking it away in solid form. There are two main approaches: (1) in-situ mineralization involves capturing CO_2 (via direct air capture or from point sources), dissolving it in water, and injecting it deep underground into reactive rock formations, typically basalt or ultramafic rocks, where it reacts to form solid carbonates; and (2) ex-situ mineralization, often called enhanced rock weathering, spreads finely crushed silicate or carbonate-rich materials (e.g., olivine, peridotite, limestone waste) over land or in reactors, allowing CO_2 uptake through natural weathering enhanced by moisture. This method accelerates a slow geological process into a viable carbon removal pathway.[85] A study demonstrated the viability of integrating mineral carbonation with direct air capture under ambient conditions by using coal fly ash and concentrated aqueous alkali carbonate solutions as a reusable solvent.[86] Experimental results indicate that the carbonation process was most effective in strongly alkaline environments, with up to ~80% of the calcium in the fly ash converted to calcium carbonate within one hour using a 1.9 M sodium carbonate solution. Based on these findings, a direct air capture-mineralization system operating entirely at atmospheric temperature and pressure was proposed. Techno-economic and life cycle analyses estimated that this approach could achieve a levelized cost of $116-133 per ton of CO_2 sequestered (in 2019 USD), with associated greenhouse gas emissions ranging from 0.03 to 0.25 tons of CO_2-equivalent per ton of CO_2 captured.[86]

3.4.2 *Feasibility and future directions*

Other emerging methods of direct air capture beyond traditional sorbent-, solvent-, and electrochemical-based systems offer unique technical advantages and promising energy profiles. Cryogenic direct air capture, for example, takes advantage of the relatively high freezing point of CO_2 by cooling air to temperatures where CO_2 solidifies, allowing for its separation from other atmospheric gases. While historically used in air separation, it has only recently been adapted for ambient CO_2 removal in cold environments or in conjunction with low-temperature waste streams. A notable development by Kar et al.[84] demonstrated a cryogenic direct air capture system integrated with liquefied natural gas regasification to harness existing cold energy. This approach significantly cuts energy use and costs, achieving capture capacities of up to 5.5 mmol CO_2 per gram of sorbent and an estimated cost as low as $68 per ton of CO_2, approximately one-third of that for conventional direct air capture. Meanwhile, biological or bio-hybrid direct air capture systems leverage photosynthetic or carbon-fixing microorganisms, such as cyanobacteria or algae, either freely growing or immobilized in scaffolds.[87] For instance, Dranseike et al.[81] created hydrogel-based living materials embedded with cyanobacteria capable of continuous CO_2 sequestration through both biomass formation and microbially induced carbonate precipitation. These materials remained active for over a year and demonstrated stable carbon uptake, suggesting great potential for low-maintenance, scalable direct air capture strategies, especially in built environments.

Photocatalytic and mineralization-based direct air capture pathways, while often coupled with traditional capture stages, expand the utility of direct air capture by converting or locking away CO_2. Photocatalytic systems use solar energy not just to release CO_2 from a sorbent but also to immediately convert it into syngas via light-activated catalysts.[83] Kar et al.[84] developed a dual-bed flow reactor in which amine-supported silica first captured CO_2 from ambient air, followed by a solar-driven conversion over a silica/alumina-titania-cobalt photocatalyst, producing syngas without the need for high temperatures or pressures. This system is designed to operate on a diurnal cycle, capturing

CO_2 at night and converting it during the day, offering an energy-efficient, product-oriented carbon capture solution. In contrast, mineralization-based direct air capture aims for permanent CO_2 storage by forming solid carbonates either underground or through enhanced rock weathering on the surface. Ragipani et al.[86] showed that fly ash combined with concentrated sodium carbonate under ambient conditions achieved up to 80% carbonation efficiency within one hour. Their techno-economic and life cycle assessment estimated a cost of $116-133 per ton of CO_2 removed, with very low net emissions. Future directions of emerging direct air capture systems focus on improving energy efficiency, scalability, and integration with existing infrastructure. Innovations include co-locating systems with industrial processes, developing advanced materials (e.g., cold-tolerant sorbents, engineered microbes, efficient photocatalysts), and designing modular, renewable-powered units.

3.5 *Comparative overview*

Figure 4 provides a comparative assessment of solvent-based, solid sorbent-based, and electrochemical direct air capture systems across six critical performance dimensions: CO_2 uptake capacity, regeneration energy efficiency, stability, scalability, technical maturity, and cost potential. Each technology displays distinct strengths and limitations that affect its suitability for widespread deployment.

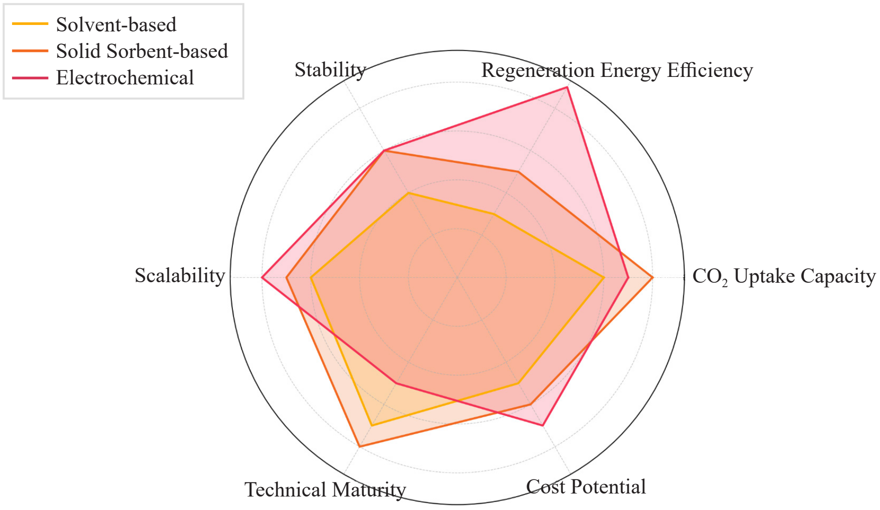

Figure 4. Feasibility comparison of solvent-based, solid sorbent-based and electrochemical direct air capture technologies

Solvent-based systems, such as those using potassium hydroxide or amine solutions, demonstrate moderate CO_2 uptake and technical maturity due to their well-established use in flue gas capture. However, they are hindered by high regeneration energy demands, primarily due to the thermal requirements for solvent recovery, and moderate long-term stability concerns such as solvent degradation and evaporation losses.

Solid sorbent-based systems, including amine-functionalized porous materials, offer a strong balance of high CO_2 uptake capacity, relatively lower regeneration energy, and promising scalability. Their solid-state configuration enhances stability and facilitates modular deployment, making them attractive for direct air capture. However, some materials still face challenges with oxidative or thermal degradation over extended cycles.

Electrochemical direct air capture systems, although currently at a lower technical maturity, stand out for their high regeneration efficiency, as they bypass thermal energy in favor of electricity. They also score well in terms of scalability and cost potential, especially in regions with access to renewable electricity. However, their CO_2 uptake capacity and stability under ambient conditions remain lower, and further research is needed to transition from lab-scale demonstrations to commercial viability.

Overall, solid sorbent-based systems currently present the most well-rounded profile for near-term direct air capture deployment, while electrochemical systems hold long-term promise contingent on technological breakthroughs. A hybrid approach integrating the advantages of each technology could enhance overall system performance and accelerate progress toward scalable carbon dioxide removal.

4. Conclusion

Liquid solvent-based direct air capture systems, while historically energy-intensive, are advancing rapidly through innovations in solvent chemistry and system design. Traditional KOH and amine-based solvents remain effective but face challenges like high regeneration energy and degradation. New alternatives, such as ionic liquids, deep eutectic solvents, and bio-derived amine systems, offer lower volatility, greater thermal stability, and enhanced CO_2 uptake. When coupled with low-grade heat or renewable energy, these next-generation solvents present promising, scalable solutions for more sustainable and efficient atmospheric CO_2 removal. Solid sorbent-based direct air capture systems are gaining traction due to their energy efficiency, modularity, and compatibility with renewable heat. Utilizing materials like amine-functionalized silica, zeolites, and MOFs, these systems capture CO_2 at ambient levels with lower regeneration temperatures than liquid solvents. Innovations such as laminate-supported sorbents, moisture-swing resins, and electrically driven regeneration enhance performance and scalability. Continued material innovation, process integration, and cost reduction are crucial to transitioning these technologies from lab-scale advances to widespread, climate-relevant deployment.

Electrochemical direct air capture is a promising, energy-efficient alternative to traditional carbon removal methods, offering low regeneration temperatures, modular design, and compatibility with renewable electricity. Innovations in redox-active materials, ion-exchange membranes, and low-cost flow cells have significantly improved efficiency, stability, and scalability. While challenges remain—such as material degradation and system cost—ongoing advances in reactor design and redox chemistry continue to push the field forward. With further research and integration, this approach could become a vital tool for sustainable atmospheric CO_2 removal. Emerging direct air capture methods, including cryogenic, biological, photocatalytic, and mineralization-based approaches, offer diverse pathways for CO_2 removal with unique advantages. Cryogenic direct air capture exploits low temperatures for efficient separation, while biological systems use microbes to convert CO_2 into biomass and carbonates. Photocatalytic techniques enable solar-powered CO_2 conversion, and mineralization offers permanent storage via solid carbonates. Together, these methods expand the direct air capture toolkit, showing strong potential for scalable, cost-effective, and sustainable carbon removal across varying environmental and industrial contexts.

Conflict of interest

The author declares that there are no known conflicts of interest.

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