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A Comprehensive Review of Reactive Carbon Dioxide Removal and Utilization Techniques

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Keywords:
CO_2 removal; CO_2 utilization; Climate mitigation; Atmospheric CO_2 reduction; Environmental impacts.

Highlights:

- *The review explores the importance of CO_2 removal and utilization.*
- *Classification of CO_2 removal methods.*
- *Process techniques for CO_2 removal and utilization were described.*
- *The integration between CO_2 removal and energy was explained.*
- *Economic rules of CO_2 reduction were reported.*
- *Challenges and opportunities in the field of CO_2 removal were discussed.*

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Abstract: The escalating threat of climate change demands urgent action to address rising levels of atmospheric CO2. This article reviews reactive CO2 removal and utilization techniques, including chemical, electrochemical, mineralization, carbonation, photo-catalysis, biological, and membrane separation methods. It examines their classification, mechanisms, technological advancements, integration with renewable energy, and related economic and policy frameworks, providing insights for researchers, policymakers, and industry experts. The review aims to offer valuable insights to researchers, policymakers, and industry specialists in the field of climate change, providing a detailed summary of the current state of CDR and CDU technologies. It evaluates the mechanisms and processes involved in CO2 capture, highlighting recent technological innovations and their integration with renewable energy sources to ensure sustainability. The economic and policy dimensions of these technologies are also examined, emphasizing the need for supportive regulatory frameworks and financial incentives to foster widespread adoption. Challenges related to scaling up CO2 capture and utilization are thoroughly discussed, including issues of cost, scalability, and technological barriers. The review highlights the immense energy requirements of large-scale CO2 operations and the importance of finding sustainable energy solutions to avoid counterproductive emissions. It also addresses the role of public awareness and community participation in advancing these technologies and achieving tangible climate benefits. The study concludes by highlighting recent progress in reducing costs, enhancing effectiveness, and increasing investment in carbon dioxide removal (CDR) and carbon dioxide utilization (CDU) technologies. It also identifies areas needing further research, such as cost reduction, efficient solutions, and environmental impacts. This review provides a thorough assessment of both opportunities and challenges, advancing CDR and CDU technologies toward a sustainable future.

مراجعة شاملة لتقنيات إزالة ثاني أكسيد الكربون التفاعلية والاستفادة منه

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الخلاصة
يتطلب التهديد المتزايد والمتصاعد لتغير المناخ اتخاذ تدابير عاجلة وفعالة للتخفيف من ارتفاع مستويات ثاني أكسيد الكربون في الغلاف الجوي. تقدم هذه المقالة نظرة عامة شاملة على تقنيات إزالة ثاني أكسيد الكربون (CDR) واستخدامها (CDU) المستخدمة على نطاق واسع، مع فحص جدواها وكفاءتها واستدامتها. يتضمن الاستكشاف مجموعة متنوعة من الأساليب، بما في ذلك البيولوجية والكيميائية. الغرض من المراجعة هو تقديم معلومات قيمة يمكن أن تكون مفيدة للباحثين وصانعي السياسات والمتخصصين في الصناعة في مجال تغير المناخ، مع الهدف النهائي المتمثل في الحفاظ على الكوكب للجمهور المستهدف. وبهذه الطريقة، تساهم هذه الدراسة، من خلال ملخصها الموجز للأبحاث الحالية في CDR وCDU، في تقدم هذه التقنيات وإمكاناتها للاستخدام في مستقبل مستدام اجتماعيًا، وتقييم شامل للفرص والتهديدات لمواصلة تطوير هذه التقنيات. بالإضافة إلى الاقتراحات والتوصيات المفيدة للتحسين. علاوة على ذلك، يتم تناول الجوانب الاقتصادية والآثار السياسية المرتبطة بتقنيات إزالة ثاني أكسيد الكربون هنا، مع التركيز على الأطر التنظيمية الداعمة المطلوبة والحوافز المالية لتعزيز اعتمادها على نطاق واسع. كما تتم مناقشة دور التوعية والمشاركة العامة، مع تسليط الضوء على أهمية المشاركة المجتمعية في تحقيق تقدم ملموس. لا تزال العديد من تقنيات CDR و CDUتواجه مشكلات تتعلق بالتكلفة وقابلية التوسع والعقبات التكنولوجية، والتي قد لا يجادل فيها هذا البحث. على الرغم من أنه يتضمن أيضًا اعتبارات تتعلق بالتقدم المحرز في السنوات الأخيرة، ويذكر انخفاض التكلفة، وزيادة الفعالية، ونمو الاستثمارات، إلا أنه يمكن للمرء أيضًا رؤية الاتجاهات التي تتطلب تحقيقات أعمق بما في ذلك التكاليف الأكثر فعالية للتكنولوجيات، والبحث عن حلول مستدامة وفعالة، والنظر بفعالية في القضايا البيئية المحتملة.

الكلمات الدالة: إزالة ثاني أكسيد الكربون، واحتجاز ثاني أكسيد الكربون، والتخفيف من آثار تغير المناخ، والحد من ثاني أكسيد الكربون في الغلاف الجوي، والتأثيرات البيئية.

1.INTRODUCTION

The increased concentration of Carbon dioxide (CO_2) in the atmosphere has emerged as a serious global issue, affecting climate change, oceanization, and ecosystem imbalance. Anthropogenic activities, such as the use of fossil fuels and industrial processes, the burning of fuel, and deforestation, among others, have raised CO_2 emissions concentrations, which are currently at the highest levels they have ever been in recorded human history. From data by the Intergovernmental Panel on Climate Change (IPCC), the atmospheric levels of CO_2, the main GHG, have risen to almost 50% of their pre-industrial level, paralleled by a rise in global temperature and a host of negative environmental consequences [1]. In response to this, scientists and engineers in the scientific and engineering fields have intensified their efforts in the quest to develop and implement carbon dioxide removal (CDR) techniques. All these strategies have the potential not only to reduce CO_2 concentration in the atmosphere or capture it and store it elsewhere, but also to reduce emissions. At the same time, Carbon Dioxide Utilization (CDU) technologies have emerged, with the main target being the use of captured CO_2 to produce valuable goods, such as synthetic fuels, chemicals, and construction materials. This approach is beneficial because it reduces CO_2 levels while simultaneously creating utility by producing useful commodities [2]. Reactive CO_2 capture and conversion has been identified as one of the potential development paths in the CDR and CDU technologies. Unlike conventional methods that merely sequester CO_2, reactive approaches involve chemically transforming CO_2 into stable compounds or integrating it into chemical processes, thus offering a dual benefit: reducing emissions while manufacturing goods in high demand. These techniques involve chemical, biological, and electrochemical processes, each with its own merits and drawbacks [3, 4]. Specifically, reactivity-based technologies that work on the principle of chemically fixing CO_2 include chemical looping, mineral carbonation, and electrochemical reduction of CO_2. For instance, mineral carbonation involves changing the mineral's physical and chemical structure using a method similar to the rock's weathering process, which forms stable carbonates, whereas electrochemical CO_2 reduction captures CO_2 and turns it into valuable products such as hydrocarbons or alcohols. Similarly, there are biologically based strategies, such as algae production, which utilize CO_2 to produce biomass that will eventually be used in biofuels and other green products [5]. However, several difficulties persist in the realm of reactive CO_2 removal and utilization technologies, which have advanced considerably in recent years. These include high energy costs entailed in some processes, problems of scale-up, and the development of better and more efficient catalysts and materials for the accomplishment of reactions. In addition, the fact that the use of some of these technologies is still more applicable on a small scale, as large-scale deployment entails additional costs, and some technologies are still in the research phase [6]. The objective of this review is to present a thorough evaluation of the latest developments in reactive CO_2 removal and utilization methods. It examines the fundamental ideas, the several technologies that have been created thus far, and their individual benefits and drawbacks. The evaluation also examines potential areas of overlap between various approaches and the future paths that these technologies need to take in order to become more practical for large-scale applications. This study aims to advance knowledge of how reactive CO_2 removal and utilization might be crucial in tackling global climate concerns and advancing a circular economy by highlighting recent developments and successes.

2.IMPORTANCE OF CO2 REMOVAL

Carbon dioxide (CO_2) emissions resulting from increased human activity significantly impact the Earth's climate. The fossil fuel industry's energy production generates CO_2, leading to substantial research on mitigating these effects through CO_2 capture and storage technologies, including new or improved coal-fired power plants [7, 8]. From November 30 to December 11, 2015, the Paris climate conference was held at the Le Bourget Exhibition Centre. Nations have since implemented strict environmental regulations to raise public awareness and address the harmful effects of CO_2 and other greenhouse gases. Before the Paris conference, China pledged to peak CO_2 emissions around 2030 and aimed for a 60% to 65% reduction in CO_2 emissions per unit of GDP from 2005 to 2030. Additionally, China aims to source 20% of its primary energy consumption from non-fossil sources and increase its forest reserves by 4.5 billion cubic meters compared to 2005 [9, 10]. Since 1980, global surface temperatures have risen alarmingly, as shown in Fig. 1.

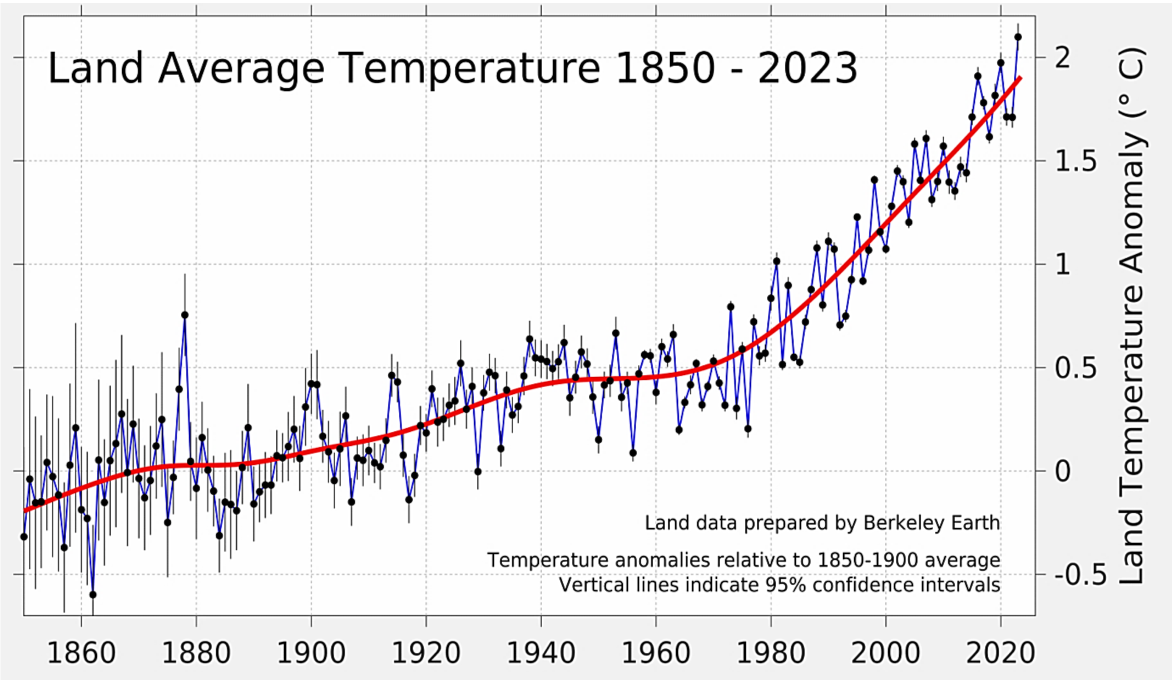

Fig. 1 Average Temperature Rise Since 1880 [11].

The international community will prioritize efforts to reduce CO_2 emissions and absorption in the coming decades. Thus, innovative technologies for reducing emissions and absorption will be a key focus [12]. To tackle climate change, sustainable energy sources and strategies to mitigate greenhouse gas emissions are crucial [13, 14]. Table 1 highlights the importance of CO_2 removal in various applications, with more details in the references. Moreover, they involve the execution of policies and regulations that are specifically formulated to encourage the use of sustainable energy sources. An instance of this is the significant impact that the implementation of electric vehicles (EVs) can have on reducing greenhouse gas emissions associated with transportation [18]. However, it is imperative to acknowledge the positive and negative tendencies that accompany this transition [19].

Table 1 Examples of the Importance of CO_2 Removal.

Application	Importance	References
Climate Change Mitigation	CO_2 removal is crucial for mitigating climate change by reducing the concentration of greenhouse gases in the atmosphere, which can help limit global temperature rise and its associated impacts.	[15]
Ocean Acidification	The magnitude of ocean acidification and the associated uncertainty at a specific stabilized temperature level can be determined by simulations that incrementally adjust GHG emissions to achieve the same stabilized warming level.	[16]
Carbon Capture and Storage (CCS)	Carbon capture and storage initiatives, which seek to prevent CO2 emissions from industrial processes and power plants from entering the atmosphere, rely heavily on CO2 removal technologies.	[17]

3.MECHANISMS AND PROCESSES OF CO2 CAPTURE

Commercial CO_2 removal from ambient air began in the 1930s to prevent dry ice formation in cryogenic air separation facilities, which caused equipment fouling [20]. Since the 1960s, CO_2 capture in the US and Canada has focused on CO_2-enhanced oil recovery (EOR). Marchetti first proposed the concept of CO2 capture and storage for mitigating CO2 emissions in 1977 [21]. A CO_2 capture system aims to produce a concentrated CO_2 stream for transport and storage or utilization. Direct transport of low-concentration CO_2 streams is impractical due to high energy and cost requirements. Thus, the choice of capture system depends on factors such as fuel type, gas stream pressure, and CO_2 concentration [22, 23]. While various reduction strategies exist, many are economically unfeasible. Given the ongoing reliance on fossil fuels and increasing global energy demand, carbon dioxide capture and storage (CCS) is a promising approach for mitigating CO_2 emissions [24, 25]. Figure 2 illustrates the three main technologies for CO_2 capture from fossil fuel combustion facilities [26]. Achieving a high capture efficiency from diverse industrial emission sources requires the selection of appropriate technologies; this is contingent on feed stream conditions (e.g., flue gas composition, stream temperature, gas flow rate, and CO_2 concentration, as well as economics), targeted production specifications (e.g., CO_2 purity and transport pressure), and discharged standards (e.g., the presence of H_2S, SO_x, and NO_x compounds) [28]. Table 2 provides an overview of various mechanisms and processes for CO_2 capture, along with specific examples, associated statistics, and references to scholarly articles supporting the information provided. DAC technologies are energy-intensive due to the direct extraction of CO_2 from the environment, contributing to approximately two-thirds of the total technology costs. The capture and compression of CO_2 can increase the cost per watt-hour of energy from fossil fuel power by 21–91% [11]. DAC is most effective at point sources, such as extensive renewable or fossil fuel facilities [41]. Separation processes, including evaporation, drying, distillation, and crystallization, are vital in various industries and account for about 10-15% of global energy consumption [42]. Various methods for CO_2 capture, including sorbent, electrochemical, and membrane technologies, are used in DAC systems. Biological CO_2 capture is primarily achieved by plants, microbes, and microalgae. Figure 3 shows the bicarbonate pool's role in capturing CO_2 for photosynthesis. Microalgae, which operate in high-pH environments and exhibit rapid growth, efficiently convert CO_2 into biomass, though they require substantial land. Marine incubation offers a viable nature-based DAC approach, with microalgae demonstrating higher CO_2 conversion efficiency compared to terrestrial plants [43].

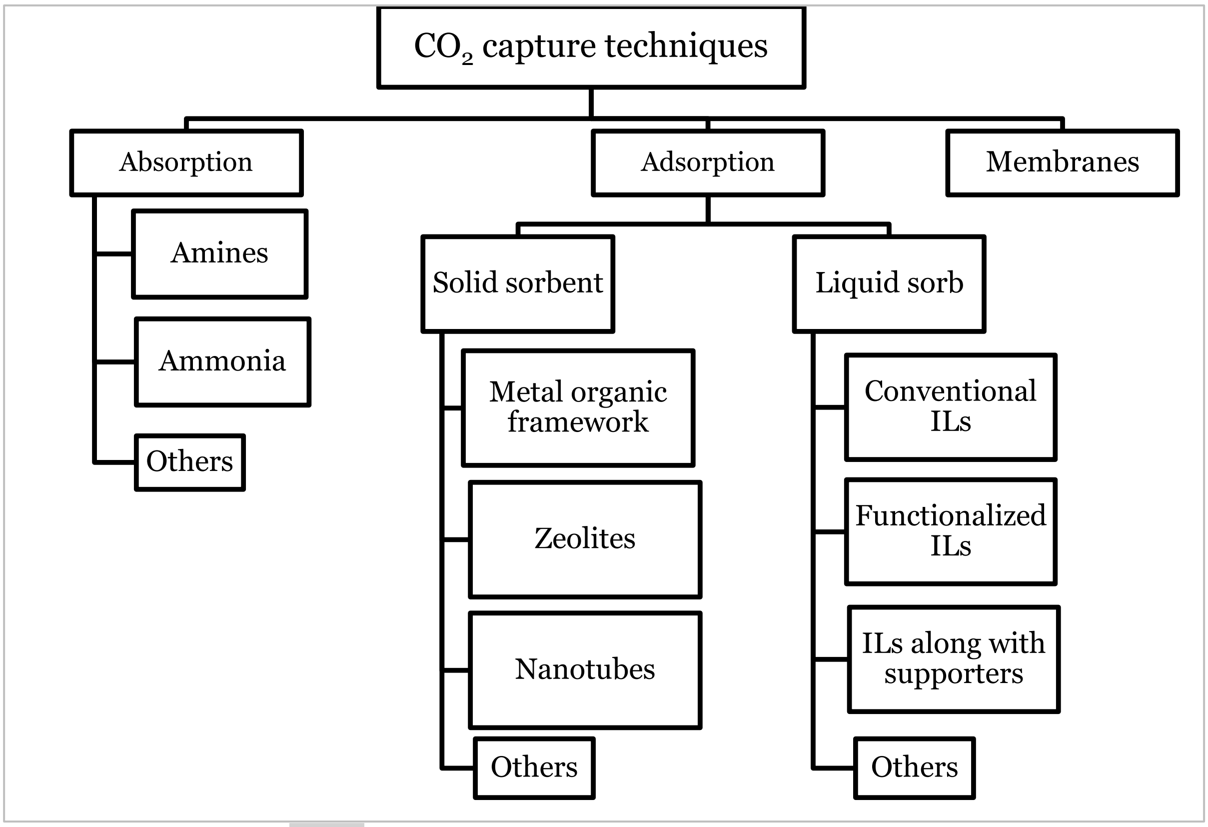

Fig. 2 Classification of CO_2 Capture Techniques [27].

Table 2 Mechanisms and Processes for CO_2 Capture.

Mechanism/Process	Examples	Statistics	Refs.
Biological Carbon Capture	Afforestation and reforestation	Forests sequester 2.4 billion metric tons of CO_2 annually	[29]
	Ocean fertilization	Estimated potential to sequester 1-2 billion metric tons of CO_2 per year	[30]
	Bioenergy with carbon capture and storage (BECCS)	BECCS has the potential to remove 10 gigatons of CO_2 annually by 2050	[31]
Direct Air Capture (DAC)	DAC using solid sorbents	Estimated cost of $94-232 per ton of captured CO_2	[32]
	Amino acid salt solutions for DAC	Potential to capture CO_2 at a cost of $100-200 per ton	[33]
	DAC with advanced membrane technology	Projected cost of $100-200 per ton of captured CO_2	[34]
Carbon Capture and Storage (CCS)	Post-combustion capture	Over 20 large-scale CCS facilities are in operation globally	[35]
	Pre-combustion capture	Has the ability to remove as much as 90% of carbon dioxide gas from IGCC power stations	[36]
	Oxy-fuel combustion capture	Up to 90% of CO_2 emissions can be captured from oxy-fuel combustion processes.	[37]
	Industrial capture and storage	Estimated potential to capture over 7 billion metric tons of CO_2 per year from industrial sources by 2050	[38]
Enhanced Weathering	Spreading crushed silicate rocks on land	Potential to sequester 1-4 billion metric tons of CO_2 annually	[39]
	Accelerating natural weathering processes in minerals	Enhanced weathering could remove 0.5-4 $GtCO_2$ per year by 2100	[40]

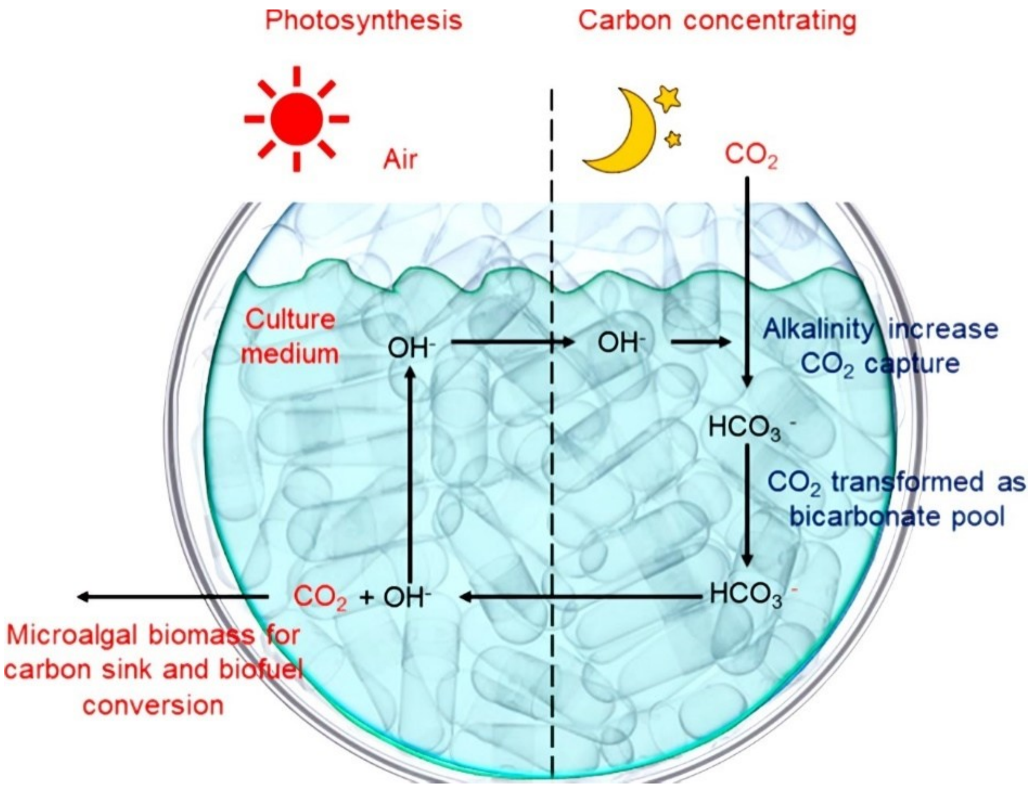

Fig. 3 Significance of the Bicarbonate Pool in the Effective Collection of CO_2 from the Atmosphere and the Quick Delivery of Carbon for Photosynthesis [41].

4.CLASSIFICATION OF REACTIVE CO2 REMOVAL APPROACHES

There are various approaches to categorizing reactive CO_2 removal methods. One widely used categorization is based on the mechanism by which these methods remove CO_2 from the atmosphere. Here are some common categories [44]:

4.1.Chemical Reaction Approach

Chemical reactions are used to capture and store CO_2, such as in carbon capture and storage (CCS), where CO_2 is captured from power plant emissions and stored underground, and in direct air capture (DAC), where chemicals bind and remove CO_2 directly from the atmosphere. A regenerable solvent can effectively absorb CO_2 post-combustion, producing a concentrated CO2 stream for sequestration; however, significant energy is needed for solvent regeneration [27]. Monoethanolamine (MEA) is a common absorbent with a regeneration energy of 3.2–4.0 MJ per kg of CO2 [45]. Using a phase change solvent that undergoes a phase transition after CO_2 absorption, forming a CO_2-rich and a CO_2-lean phase, can reduce energy demand as only the CO_2-rich phase requires regeneration [46]. In chemical absorption, the exhaust CO2 reacts with a solvent to form a weakly bonded intermediate, which is restored by heating. The CO_2-containing gas reacts with the absorbent in a packed bed absorber column. The CO_2-rich absorbent is then regenerated in a stripper and recycled [47]. The net CO_2 emissions from the stripper are transferred to liquefaction, transportation, and storage. Amine-based solvents, such as MEA, are the most frequently used in chemical absorption due to their high CO_2 absorptivity.

4.1.1.pH Swing

The pH swing approach enhances mineral carbonation rates by alternating between acidic and basic conditions. Magnesium and calcium dissolve more quickly in acidic environments, while basic conditions favor carbonate precipitation [48]. Li et al. [49] demonstrated this method with serpentine, using NaOH to precipitate magnesium carbonate after an acid leaching phase with HCl. Effective carbonation was achieved by pre-treating serpentine at 650 °C, converting 98.8% of Mg^{2+} in the liquor, and producing stable hydro-magnesite ($Mg_5(CO_3)_4(OH)_2(H_2O)_4$) up to 450 °C. The gas pressure was unspecified, and the acids and bases were derived from electrolyzed ocean water. Kodama et al. carbonated steelmaking slag using a strong acid-weak base solution ($HCl/NH_4^+/NH_3$) at various temperatures (40-90 °C), achieving up to 60% conversion. Ammonium chloride facilitated calcium dissolution and ammonia byproduct formation, although the process was costly due to the need for NH_3 recovery [50]. Rashid et al. [51] noted high energy consumption due to the need for water evaporation before compound recovery. Bu et al. [52] reported that bipolar electrodialysis at ambient temperatures in HCl/NaOH systems required 372–569 kWh/t of NaOH, reduced energy use compared to conventional methods. Stokreef et al. [53] found that NH_4HSO_4/NH_4OH systems needed 1300 kWh/t CO2, but Sanna et al. [54] suggested that liquid-liquid extraction could cut energy consumption by 35% (845 kWh/t CO2).

4.1.2.Feed Activation

Activation of feedstock enhances carbonation processes through thermal, mechanical, chemical, or hybrid methods. Emerging research on carbon mineralization [55, 56] has utilized feed activation [49, 57, 58], though its efficacy remains under-evaluated. Activation, while increasing surface area, is costly and energy-intensive. For example, up to 75% of the energy in carbonation processes is consumed by reducing feedstock particle size [59]. Alternative feedstocks, such as fly ash and boiler bottom ash, may reduce this energy demand due to their fine particle size. Maroto-Valer et al. [60] assessed the carbonation potential of activated serpentine via chemical and thermal activation. Thermal activation at 300 °C and 650 °C had minimal impact on surface area, while steam activation at higher temperatures significantly improved carbonation conversion by 60% at 126 atm and 155 °C within one hour. Despite this, the process remains costly. Chemical activation with acids increased the surface area from 8 m²/g to 330 m²/g due to magnesium extraction, which, although not enhancing carbonation extent, reduced energy demands [61]. Carbon microstructures for membranes, typically produced by pyrolyzing thermosetting polymers at 500-1000 °C in the absence of oxygen, are enhanced when supported on porous substrates. These microstructures, with internal diameters ranging from less than 1 nm to several nanometers, allow for effective molecular sieving. Recent advances include the use of stacked graphene oxide nanosheets on a PEBA copolymer substrate, achieving a CO_2 permeability of 100 Barrer and a selectivity of 91 for CO_2/N_2 mixtures [62]. Additionally, single-wall carbon nanotubes show twice the CO_2 capacity of activated carbon [63].

4.2.Electrochemical Reduction Approach

The electrochemical reduction of CO_2 is a promising approach for converting CO_2 into value-added chemicals and fuels, thereby addressing both energy storage and carbon utilization challenges. This process typically involves the use of an electrocatalyst to facilitate the reduction of CO_2 at the cathode, while water oxidation occurs at the anode. Various products can be obtained depending on the electrocatalyst, including carbon monoxide (CO), formic acid (HCOOH), methanol (CH_3OH), and hydrocarbons, such as ethylene (C_2H_4) and ethanol (C_2H_5OH) [64]. One of the most studied catalysts is copper, which is known for its ability to produce a wide range of hydrocarbons and oxygenates. Copper catalysts, particularly in their nanoparticle form, have demonstrated high selectivity and efficiency in converting CO2 to ethylene and ethanol, making them a focal point of research [65]. The reaction conditions, including the electrolyte composition, pH, and applied potential, significantly influence the selectivity and efficiency of the CO_2 reduction process. For instance, the use of ionic liquids as electrolytes has been shown to enhance the selectivity for CO and formic acid due to their ability to stabilize CO_2 intermediates [66]. Additionally, the development of gas diffusion electrodes has improved the mass transport of CO_2 to the catalyst surface, resulting in higher current densities and enhanced reaction rates [67].

Despite the progress, several challenges remain in scaling up the electrochemical reduction of CO_2 for industrial applications. These challenges include the high overpotentials required to drive the reactions, the durability and stability of the catalysts, and the need for efficient separation and purification of the products. Advanced catalyst design, including the use of bimetallic and alloy catalysts, has shown promise in addressing some of these issues by reducing overpotentials and improving catalyst stability [68]. Furthermore, integrating renewable energy sources, such as solar or wind, with electrochemical CO_2 reduction systems could provide a sustainable pathway for large-scale implementation [69].

4.3.Mineralization Approach

The processes involved in the mineralization of CO_2 from silicate ores are typically categorized as direct or indirect. In essence, direct carbonation involves a single stage of direct reaction between CO_2 and the mineral source, while indirect carbonation involves the decomposition of the process into several steps. Additional facets of the mineralization process that have been the subject of recent research endeavors aimed at enhancing reaction rates through feed activation [70] employ diverse reactor technologies and investigate potential applications for carbonation products in industry, resale, and recycling. Additionally, these studies aim to enhance the economic viability of the mineralization process as a whole [71]. There are two separate applications for the carbonate compounds that are produced through the mineral carbonation of CO_2. These encompass both high-end low-volume uses and low-end high-volume uses. Nevertheless, to be considered commercially viable, these products must meet specific quality standards and specifications. Examples of such parameters include a reasonable particle size and a low level of contaminants [72]. Carbonate minerals are presently utilized in a variety of industrial applications (Figure 4). They have been discovered to be beneficial in the fabrication of paper and fiber, the pharmaceutical industry, the agricultural sector, and the production of refractory metals. The construction industry provides the most appropriate application opportunities for mineral carbonates and the overall reduction of CO_2 emissions [71]. Table 3 summarizes different mineralization techniques for CO_2 removal.

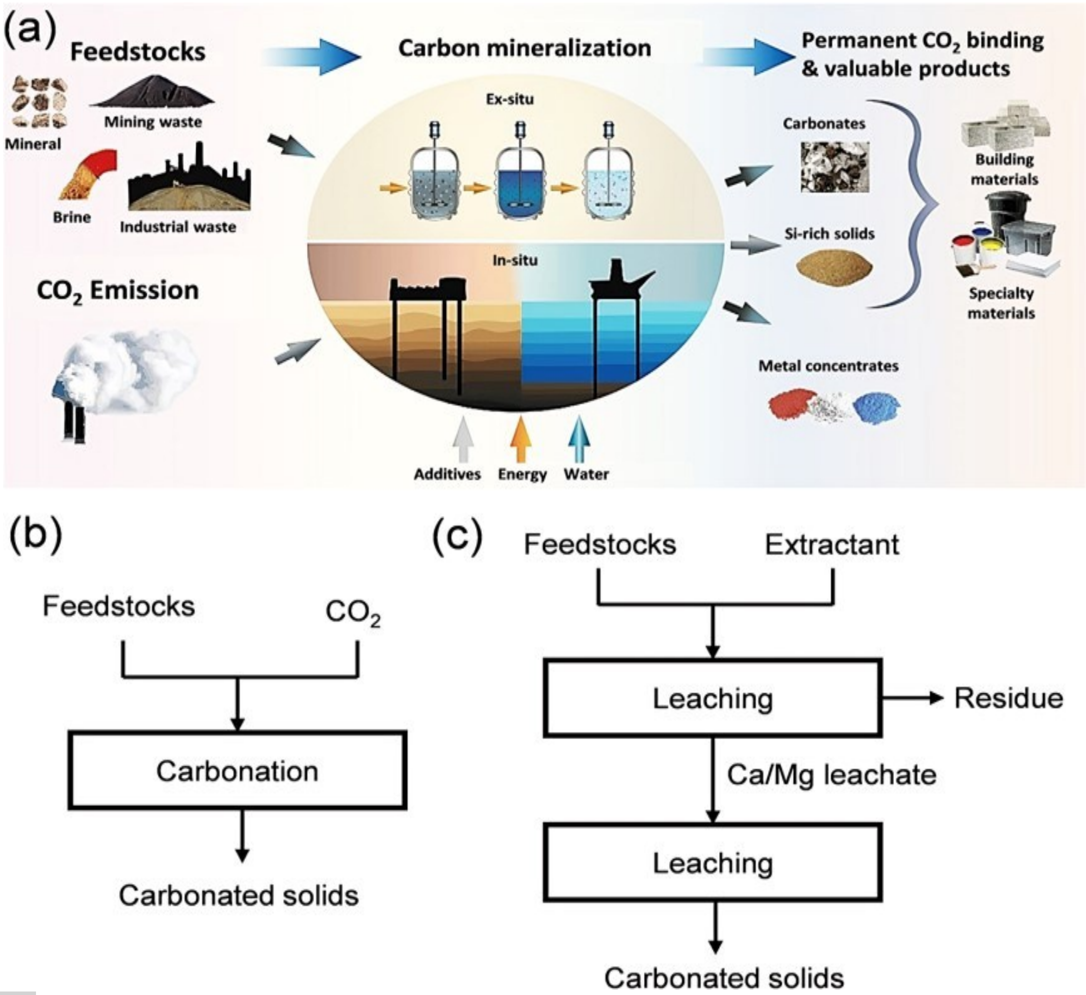

Fig. 4 (a) Carbon Mineralization from Various Feedstocks to Different Products. Image Courtesy of Florent Bourgeois, Laboratoire de Genie Chimique; Au-Hung Park and Xiaozhou Sean Zhou, Columbia University. Process flow Charts of (b) Direct and (c) Indirect Carbonation [73].

Table 3 Mineralization Techniques for CO_2 Removal.

Mineralization Technique	Description	Refs.
Mineral Carbonation	The process involves the reaction of CO_2 with metal oxides to produce stable carbonates, such as magnesium or calcium carbonates. The process can be executed with either industrial refuse materials or natural minerals.	[74]
Accelerated Weathering	Carbon dioxide is dissolved in water more efficiently by utilizing natural weathering processes, which result in the formation of carbonates. The methodology described above applies to silicate materials, such as serpentine and olivine.	[75]
Oceanic CO_2 Sequestration	This technology provides a variety of benefits, such as the availability of marine storage sites, which are not the case with terrestrial sites, which are limited. As with terrestrial sequestration, marine sequestration is also capable of storing CO2 for an extended period of time due to the unique marine environment.	[76]
Biomimetic Mineralization	Draws inspiration from biological processes to develop synthetic materials that can efficiently capture and convert CO_2 into stable minerals. Examples include using enzymes or bio-inspired catalysts for mineral formation.	[77]

4.4.Carbonation Approach

4.4.1.Direct Carbonation

There are two overarching approaches to direct carbonation: aqueous and dry gas-solid. Reducing the price of processing requires a better understanding of the processes that restrict the carbonation rate, which includes investigating the reaction at the particle-reactant interface. The exothermic nature of the overall reaction is facilitated by the thermodynamic advantage of carbonates over silicate minerals [78]. An essential direct aqueous carbonation route was proposed by the U.S. American National Energy Technology Laboratory (NETL). Sodium chloride and sodium bicarbonate are employed in this NETL process to improve the reaction kinetics. Additional process conditions are dependent on the feedstock. For example, wollastonite is carbonated at a temperature of 100 °C and a pressure of approximately 40 bar [79]. Supplementary cementitious materials (SCMs) or aggregates in concrete products can be produced from carbonate products that undergo direct carbonation [80].

4.4.2.Dry Gas-Solid Carbonation

Direct carbonation of dry gas and solids involves CO_2 reacting with solid mineral cations, benefiting from heat recycling but often suffering from slow reaction rates [81]. Research, such as Larachi et al.'s in situ carbonation of chrysotile in dry environments with 10% H2O, showed that higher carbonation rates occur in the presence of water, with magnesium carbonate hydrate as the end product [82]. Cesium feed impurities also enhance chrysotile carbonation capacity [83]. Studies have explored using fly ash for CO_2 fixation through direct gas-solid or aqueous MC technology, noting that solid-to-liquid ratio, reaction time, pressure, and stirring speed are critical for stable carbonate formation [84]. While research on fly ash with high alkaline oxide content has increased, the carbonation process is significantly influenced by the type of calcium source in fly ash. Anhydrite particles in fly ash reduce carbonation efficiency if desulfurization residues are present [85]. Calcium from lime and portlandite reacts with CO_2 more quickly than other sources, and the presence of Na2CO3 enhances carbonation efficacy at 140°C and 20 bar [86].

4.4.3.Aqueous Carbonation

Aqueous mineralization schemes capitalize on the elevated rates of carbonation reactions that transpire within aqueous mineral sediment. The aqueous carbonation process route proposed by NETL [87] is widely regarded as a precisely defined route for mineral carbonation [81, 88]. As a result, it is frequently employed as a foundational process in investigations pertaining to other facets of carbonation. In recent studies, there has been a greater emphasis on scrutinizing the chemical activities that lead to silicate dissolution and carbonate precipitation, with the aim of refining these conditions. Maroto-Valer et al. [60] investigated the effect of feedstock activation on serpentine reaction kinetics using an aqueous method comparable to that of NETL. An additional investigation was conducted on the carbonation of olivine in water, focusing on the reaction interface and surface, with the formation of a layer of silica passivation that inhibited further carbonation [89]. In order to enhance carbonation, the study indicated that agitation or abrasive particles, such as quartz, were useful. These particles improved particle-to-particle collisions, which in turn facilitated the exfoliation of the silica passivation layer. As byproducts, the steelmaking industry also produces a substantial quantity of slag. For each metric ton of wrought iron or steel, approximately 0.5–1 metric tons of slag are produced [90]. Initially, steel slag was considered a waste material and was disposed of in landfills. However, it is now primarily utilized as a cementitious and roadbed material to conserve space and prevent landfilling of [91]. The properties of steel slag are enhanced and stabilized after it undergoes carbonation, rendering it suitable for widespread use in construction materials [92]. The demand in the construction industry correlates with the potential utilization of materials like steelmaking slag, which is valuable for various applications, including nutrient recovery, CO_2 mineralization, wastewater treatment, and soil amendment [93]. Steelmaking slag, rich in calcium and magnesium, can sequester CO_2 through mineral carbonation, converting CO_2 into carbonates [94]. This not only enhances the slag's properties but also supports its use in cement, concrete, and roadbed material [95], making CO_2 fixation in slag a promising approach for both emission reduction and slag utilization.

4.4.4.Indirect Carbonation

Direct carbonation processes are generally slower [81]. To accelerate these processes, dividing them into smaller steps is beneficial. One such indirect method under investigation involves altering the solution's pH [96]. Indirect carbonation typically requires two steps: extracting magnesium and calcium ions and then reacting them with CO_2 to form carbonates. Successful implementation often depends on maintaining separation between these steps, as they require different pH conditions. This has led to methods such as two-stage or pH swing carbonation [97]. Sucrose has been identified as an additive that enhances vaterite formation. Studies on vaterite synthesis using sucrose often employ either solution mixing or CO_2 bubbling methods. For example, Konopacka-Łyskawa et al. [98] used NH3 to promote CO_2 absorption and incorporated various saccharides, finding that 90 mM sucrose yielded 90% vaterite. Dickinson and McGrath [99] achieved 85% vaterite with a 3 wt% sucrose concentration using the CO_2 bubbling method. P´erez-Villarejo et al. [100] synthesized 100% vaterite with 67% sucrose, though the crystals were irregular and small. Liu et al. [101] noted that sucrose accelerated vaterite formation, but the exact mechanism remains unclear. Additionally, Yao et al. [102] investigated the impact of sucrose and bovine serum albumin (BSA), finding that either 20% sucrose or 5% sucrose with BSA facilitated vaterite formation.

4.5.Photo-Catalysis Approach

Photo-catalysis for CO_2 removal leverages light-driven chemical reactions to convert CO_2 into valuable products or to enhance CO_2 capture. One prominent approach involves the use of semiconductor photocatalysts, such as titanium dioxide (TiO2) and zinc oxide (ZnO), which, under UV or visible light, can facilitate the reduction of CO_2 into hydrocarbons or alcohols [103]. These photocatalysts operate by generating electron-hole pairs upon light excitation, which then participate in redox reactions to convert CO_2 [104]. For instance, TiO_2 has been extensively studied due to its stability and photocatalytic efficiency, achieving CO_2 reduction with high selectivity for methanol and methane [105]. Advances in doping TiO_2 with elements, such as nitrogen or creating composite materials with carbon-based supports, have shown improved visible light activity and increased CO_2 conversion rates [106].

4.6.Biological Approaches

Biological approaches for CO_2 removal leverage natural processes to capture and convert CO_2. One prominent method is the use of microalgae in photobioreactors, which absorb CO_2 during photosynthesis and convert it into biomass. This process not only reduces CO_2 levels but also produces valuable by-products such as biofuels and animal feed [107]. Another approach involves soil carbon sequestration, where CO_2 is captured and stored in soil organic matter through the use of enhanced land management practices [108]. Additionally, reforestation and afforestation initiatives utilize trees and plants to sequester CO2 from the atmosphere through natural growth processes [109]. These methods contribute to mitigating climate change by removing CO2 and enhancing carbon sinks. Microalgae cultivation has been particularly noted for its efficiency in CO2 uptake and biomass production [110], while soil and forest management practices offer long-term carbon storage solutions [111]. Table 4 outlines the mechanisms by which microorganisms fix CO_2 from the air. Microbes utilize both photosynthetic and nonphotosynthetic pathways to convert atmospheric CO2 into biomass and energy [112]. The advantages of microbial CO_2 capture include efficient bioremediation, high biofixation rates, diverse product formation with minimal genetic changes, and applicability in bioprocessing. This includes bacteria, fungi, yeast, and algae [113]. Recent research focuses on converting CO_2 into value-added products using advanced biological and non-biological technologies. For instance, microbial electrochemical technologies, such as microbial electrosynthesis (MES) and microbial carbon-capture cells (MCC), can capture CO_2 while treating contaminated water and recovering valuable products. Plant-microbial fuel cells (P-MFC) utilize atmospheric CO2 in photosynthesis and consume contaminants for plant growth [114]. Microalgae, in particular, can significantly reduce CO_2 emissions and have a CO_2 fixation rate 10–50 times higher than terrestrial plants [115], making algal-based treatment a promising technology for mitigating global climate change. On the other hand, a catalyst is necessary to facilitate a CO_2 reduction reaction in electrochemical and photoelectrochemical technologies. As the final carbon product (CO_2) is a thermodynamically stable molecule, an elevated activation energy is necessary to reduce CO_2 to CO_2^- ($E^\circ = -1.90$ V *vs* SHE at pH = 7.0) [116]. Additionally, CO_2 reduction is linked to the hydrogen evolution reaction (HER), a cathodic half-reaction that takes place at a lower overpotential (E° = 0 V vs SHE at pH = 7.0) [116]. An ideal electrocatalyst is necessary to overcome this side reaction in order to accomplish CO_2 reduction, as it can lower the activation barrier of the CO_2 reduction reaction in comparison to HER [117]. Thus, it is feasible to achieve CO_2 reduction with increased reaction rates, even in the presence of minimal overpotential.

Table 4 Microbial Carbon Sequestration Through Various Pathways [112].

Input	Pathways	Enzymes	Organism
CO_2	Reductive pentose phosphate cycle (CCB) or Calvin-Benson-Bassham cycle	RuBisCO	Mycobacteria, plants, algae, cyanobacteria, and proteobacteria
CO_2	Reductive citric acid cycle (rTCA)/Reductivetricarbocylic acid cycle/Arnon Buchanon Cycle/Reverse Krebs cycle	PEP carboxylase 2Oxoglute rate synthase IsocitrateDehydrogenase Pyruvate synthase	Quaficae bacteria, green proteobacteria, sulfur bacteria.
CO_2	Wood-Ljungdahl pathway (W-L) or Reductive acetyl-CoA pathway	The dehydrogenase formate Formylmethanofuran Dehydrogenase (FMFD) and carbon monoxide dehydrogenase (CODH)	Euryarchaeota, proteobacteria, plantomycetes, spirochaetes
CO_2	3-Hydroxypropionate 4-hydroxybutyrate cycle (3HP-4HB)	Acetyl-CoA/Propionyl-CoA carboxylase	Aerobic crenarcheota
CO_2	Dicarboxylate 4hydroxybutyrate cycle (DC-4HB)	Pyruvate synthase PEP carboxylase	Anaerobic crenarcheota
CO_2	3-Hydroxypropionate bi-cycle (3-HP)/FuchsHolo cycle	Acetyl-CoA carboxylase Propionyl-CoA carboxylase	Green non-sulfur bacteria

4.7.Membrane Separation Approach

Membrane separation technologies offer a promising method for CO2 removal by selectively permeating CO2 through a membrane while allowing other gases to pass through. This approach leverages various types of membranes, including polymeric, inorganic, and mixed-matrix membranes. Polymeric membranes, such as those made from polyimides or polysulfones, are commonly used due to their relatively low cost and ease of fabrication. However, their performance can be limited by factors such as plasticization and lower selectivity for CO2 [118]. Inorganic membranes, including zeolite and ceramic-based membranes, provide high thermal and chemical stability, making them suitable for harsh operating conditions, but this often comes at a higher cost and complexity [119].

4.8.Other Technologies

4.8.1.Flow Reactor

Two studies by Huntzinger et al. [120] investigated gas-solid combustion of residue-cemented kiln particles in a packed bed reactor at ambient conditions. The packed bed was filled with compacted kiln dust, and CO2-containing gas was introduced through it. Variations in water content and CO2 concentration were tested, resulting in calcium carbonate production with conversions similar to batch reactors. However, further research is needed to separate the effects of feedstock composition from reactor operating conditions [121]. The plug-flow behavior of fixed beds, which maintains the reaction front's position, allows for a shorter reactor and reduced pressure loss compared to traditional designs. However, challenges include the interconnected nature of reactors, preventing pressure swings, and the difficulty of moving large particles between reactors. Indirect heating is less efficient due to lower mixing in moving beds compared to fluidized beds, leading to a complex temperature swing [122]. The "Hypersorption" process [123], proposed by Clyde Berg in 1946, aimed to recover propane, ethane, and ethylene from refinery off-gases. SRI International and Advanced Technology Materials, Inc. (ATMI) have recently introduced a new moving bed reactor design to reduce the energy penalty of post-combustion CO2 capture. This design completes the CO2 capture cycle by passing a sorbent through an adsorber, transition, desorber, dehydrator, chiller, and lift [124].

4.8.2.Fluidized Bed

Increasingly, studies are looking at the use of fluidized bed technology for carbonation, since it seems to be an economical way to speed up reactions at lower temperatures and pressures. The University of Wyoming is conducting an investigation into a patented carbon mineralization method that combines flue gas CO_2 and combustion fly ash [125]. A fluidized bed was utilized, consisting primarily of fly ash (SiO_2, CaO, Fe_2O_3, or MgO, with a concentration of 1050%), and combustion gas flow (N_2 with 2-6% CO_2). This endeavor is reportedly the inaugural attempt at carbonation and simultaneous direct extraction of CO_2 emissions at their source. Transporting CO_2 is a significant expense associated with implementing large-scale carbon capture and storage, which will likely necessitate the construction of a network of conduits. The elimination of conveyance requirements would result in a significant reduction in expenses. An investigation by Fagerlund et al. [126] found that magnesium hydroxide is in its nascent stages of carbonation in a supercritical state within a fluidized bed under CO_2 conditions (600 °C, 100 bar). The authors assert that the carbonate product layer, which serves as the rate-limiting diffusion barrier, will undergo decomposition and eventual elimination within the fluidized bed due to particle-particle collisions and interactions. This process will lead to ongoing exposure of unreacted core material to CO_2, ultimately increasing the maximum conversion level that can be achieved. The carbonation of Mg $(OH)_2$ was experimentally investigated by Fagerlund and Zevenhoven in a fluidized bed kiln [127]. Fluidized beds provide improved mass and heat transfer, necessitate less mass to be heated, produce dry and easier-to-handle products, and use substantially less energy than wet slurry columns. Nevertheless, in order to achieve substantial conversion yields in dry conditions, it will be necessary to operate at elevated temperatures and pressures. These conditions present an economic challenge for the mineralization of serpentine using fluidized beds. The operation of a fluidized bed with moist mineral particles, at atmospheric pressures and moderate temperatures, can capitalize on the benefits of both slurry columns and fluidized beds [128].

4.8.3.Oscillatory Baffled Reactor

Using an oscillatory baffled reactor (OBR) for CO2 removal has shown significant promise due to its enhanced mass transfer and mixing capabilities. The design of the OBR, which incorporates periodic baffles and oscillatory flow, creates a unique environment that significantly improves the dissolution of CO2. According to Pereira et al. (2014), the multiorifice oscillatory baffled column design facilitates increased contact between the gas and liquid phases, leading to more efficient CO2 absorption [129]. Ahmed et al. (2018) underscored the importance of OBR design in mass transfer enhancement, showing that the reactor's oscillatory nature significantly boosts gas-liquid mass transfer rates [130]. Avila et al. (2022) detail the design and performance characteristics of continuous OBRs, highlighting their versatility and efficiency in various applications, including CO2 capture [131]. The oscillatory motion, combined with strategically placed baffles, creates vortices and eddies that disrupt boundary layers and enhance mass transfer. This is particularly advantageous for CO2 removal, as it enables faster and more efficient capture of CO2 from flue gases or ambient air. The work by Heidaryan et al., (2023) further supports these findings, demonstrating that CO2 capture operations can be markedly enhanced in an OBR due to the intensified mixing and mass transfer rates [132]. Overall, the integration of oscillatory baffled reactors in CO2 removal processes offers a robust solution to enhancing mass transfer and reaction rates, making them a valuable asset in industrial CO2 capture and sequestration efforts. The synergy between oscillatory motion and baffled design ensures high efficiency and effectiveness, positioning OBRs as a critical technology for addressing carbon emissions and combating climate change.

5.TECHNOLOGICAL INNOVATIONS IN DIRECT AIR CAPTURE

The six major technical approaches to CO_2 removal and sequestration are as follows: direct air capture, coastal blue carbon, terrestrial carbon removal and sequestration, bioenergy with carbon capture and sequestration (BECCS), carbon mineralization, and geological sequestration. According to the National Academies of Sciences (2018) [133], Direct Air Capture (DAC) is the most extensive carbon removal technique among the six different approaches listed in Table 5.

Table 5 Technological Innovations in Direct Air Capture.

Technological Innovation	Description	Reference
Carbon Engineering's Direct Air Capture	This technology uses a series of chemical reactions to capture CO_2 from the air and convert it into a concentrated stream for utilization or storage.	[134]
Climeworks' Direct Air Capture	Climeworks has developed a direct air capture technology that utilizes a filter material to absorb CO_2 from the air.	[135]
Global Thermostat's Direct Air Capture	Global Thermostat's technology involves using large-scale adsorption systems to capture CO_2 from the atmosphere. The captured CO_2 can be used for various purposes, such as fuel production or industrial processes.	[136]
Skytree's Direct Air Capture	Skytree's technology uses a proprietary resin material to selectively capture CO_2 from the air. The captured CO_2 can be utilized in various applications, including carbon-neutral fuels and materials.	[137]
Amino Acid Salt Solutions for DAC	Amino acid salt solutions have been developed as a promising solvent for capturing CO_2 from the air due to their high selectivity and low energy requirements.	[138]
DAC with Advanced Membrane Technology	Advanced membrane technology has shown potential for separating CO_2 from air by utilizing selective membranes that allow the passage of CO_2 while blocking other gases.	[34]

These technological innovations in direct air capture demonstrate promising approaches to efficiently remove CO_2 from the atmosphere, offering potential solutions for addressing climate change. There is considerable ambivalence among policymakers and individuals seeking innovative new technologies. Concerning land use, each of the aforementioned technical approaches has its own set of advantages and disadvantages. DAC attracts considerable interest because, unlike BECCS and the Coastal Blue method, it does not impose size restrictions in terms of hectares or proximity to a coastal area [139]. DAC can capture CO_2 directly from the air using contactors featuring a substantial surface area to enhance air contact, without the need for arable land. The captured CO_2 is subsequently discharged and stored. This is accomplished by employing liquid or solid sorbents. DAC can also assist with emissions that are challenging to prevent or originate from distributed sources [139]. The annual emissions from the iron-steel industry (11%), concrete (8%), transportation (24%), and wildfires (0.8%) are among the significant contributors. Furthermore, the highest vertical concentration of CO_2 in the atmosphere, 420 ppm, is approximately 1.5 kilometres above the Earth's surface. Nearly 4 kilometres into the atmosphere, the concentration of CO_2 is approximately 0.5 percent lower [140]. DAC (Direct Air Capture) plants at sea level can effectively extract large quantities of atmospheric CO2. Currently, 19 DAC plants worldwide capture about 10,000 tonnes of CO2 per year. In the U.S., a plant with a capacity of 1 Mt of CO2/year is under development [139]. To remove 25 GtCO2 by 2030, an estimated 1,250 DAC plants, each capturing 1 MtCO2/year, would be needed, assuming carbon capture and storage increases from 0.0385 Gt/year to 20 Gt/year [141]. This estimate assumes linear growth; however, DAC technology may experience exponential growth similar to other emerging technologies. Each 1 Mt of CO2/year plant requires about 0.2 km^2 of land, equivalent to 28 soccer fields. Current DAC technologies require 1–7 tonnes of water per tonne of CO2 captured, potentially increasing to 13 tonnes with 30% humidity and monoethanolamine absorption [142]. These land and water needs significantly impact the feasibility and location of DAC plants. Currently, the economic feasibility of CO2 sequestration in geological formations largely depends on its use for enhanced oil recovery (EOR) [143]. However, industrial CO2 utilization remains minimal compared to the 32 Gt/yr emitted globally. Like point source capture technologies, DAC's commercialization relies on utilizing captured CO2. The future looks promising, with potential CO2-derived products valued at approximately $5 trillion [144]. Despite this, DAC facilities face competition from other CO2 capture methods and natural sources, which often have cost advantages. Nonetheless, DAC facilities are favored for their scalability and ability to be located near CO2 consumers, reducing transportation costs [145]. Large fans draw in the surrounding air, which is subsequently heated and treated with a chemical sorbent (solid or liquid) to extract CO_2. As demonstrated, this CO_2 is subsequently sequestered or utilized in other industries [145]. The captured CO_2 from the DAC could be utilized in agriculture, food, beverages, synthetic fuels, and even subterranean sequestration. This gives the DAC a broad market. Figure 5 illustrates the present state of DAC plants globally, in addition to Carbon Capture and Storage (CCS) establishments that capture carbon dioxide at its source, such as industrial and thermal power plants. CCS facilities are frequently integrated into industrial processes to mitigate emissions [141]. The dimensions of the DAC facility in Figure 6 are determined by the thermal energy source and the sorbent type utilized [142]. In addition to solid and liquid solvents, Plants can harness a diverse range of thermal energy sources, such as photovoltaic, geothermal, and others.

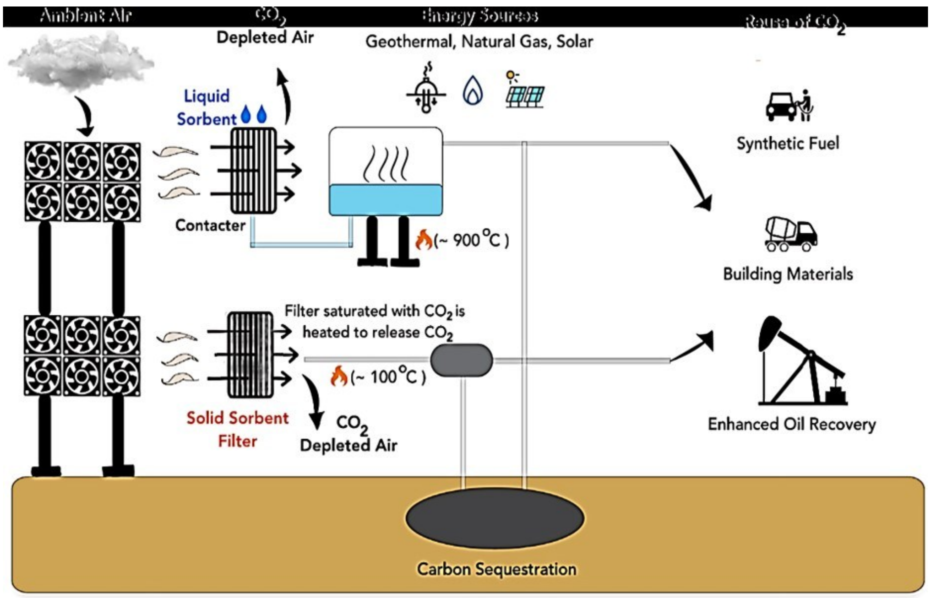

Fig. 5 CO_2 Captured from Air Using Liquid and Solid Sorbent DAC Plants, Storage, and Reuse [139].

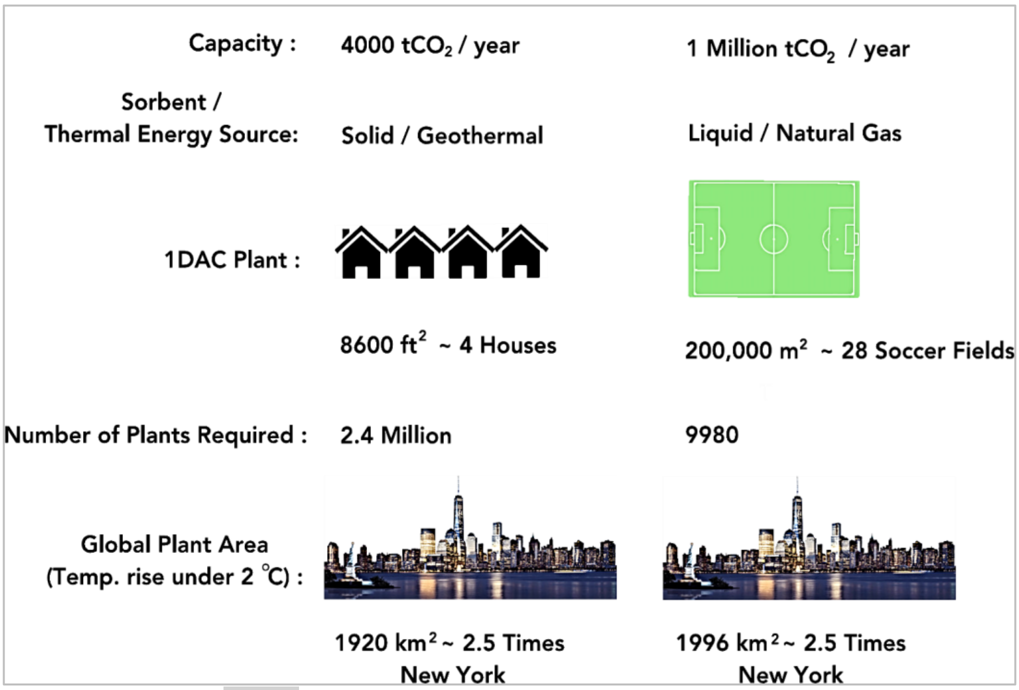

Fig. 6 DAC Plant Land Area Requirement [139].

6.INTEGRATION OF CO2 REMOVAL WITH RENEWABLE ENERGY

The utilization of renewable energy, the capture and storage of carbon dioxide, and additional technological advances to improve the efficiency of fuel and electricity have been identified as critical components in the implementation of strategies and routes to achieve the net-zero emission goal [146]. Consequently, the integration of their technologies would present an extraordinary prospect for attaining the intended state of net-zero energy output. The consumption of fossil fuels accounts for an estimated 90 percent of total carbon dioxide (CO_2) emissions worldwide. Fossil fuel-fired power facilities are considered the most substantial among these sources [147]. As industrial activities and energy demand continue to rise, it is unlikely that the combustion of fossil fuels for energy production will cease. However, CO_2 capture and storage (CCS) technologies (Figure 7) could offer a viable alternative for the continued use of fossil fuels in a more sustainable and environmentally friendly manner. Numerous initiatives have been suggested to mitigate carbon dioxide emissions, with CCS being regarded as the most feasible technological alternative, projected to account for approximately 19% of all CO_2 reduction measures by 2050 [148].

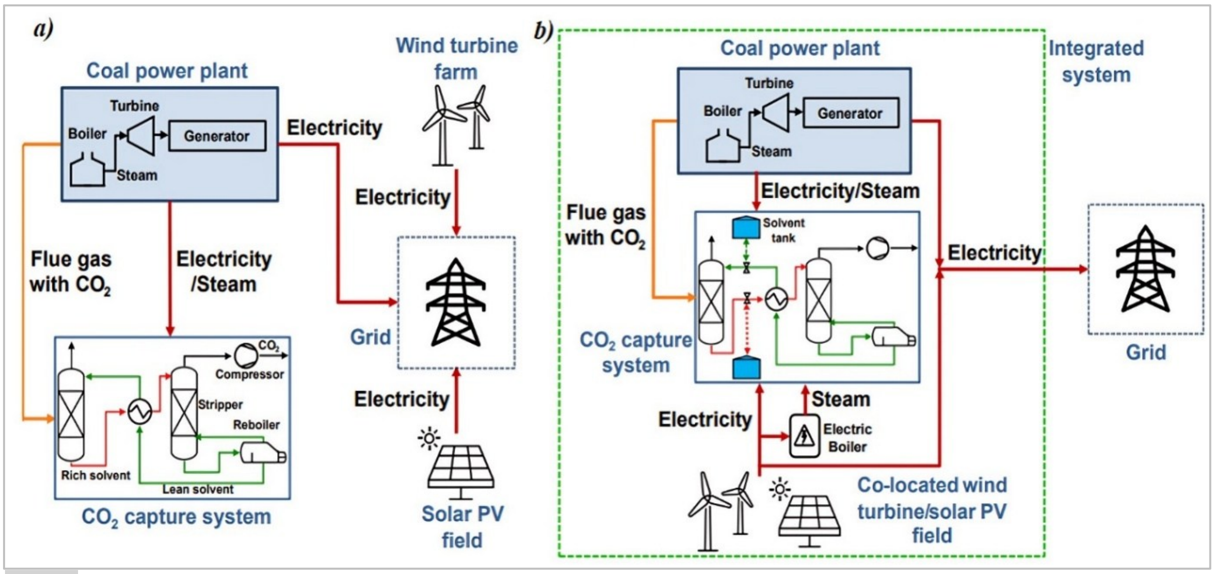

Fig. 7 Two Paradigms of Integrated Power Generation, CO_2 Capture, and Renewable Energy Systems. (a) Conventional, Non-Integrated System Configuration, and (b) Integrated System Configuration [149].

Recently, there has been talk of combining CO_2 collection with renewable energy sources to lessen the impact on power plants' energy bills. This is in response to the growing demand for more diverse power systems that incorporate renewable technology. Economic factors usually dictate that a removal efficiency of 85-95% is adequate, even though solvent-based absorption has the capability to completely eliminate CO_2 in the combustion process for energy power stations and other industrial sectors [150]. The residual quantity of carbon dioxide (CO_2) is released into the atmosphere. The concentration of CO_2 in the atmosphere will continue to rise as it mixes with CO_2 from mobile and other sources that are harder to mitigate. Therefore, in order to achieve a net-zero emission target, negative-emission technologies, such as bioenergy combined with carbon capture and storage (BECCS) and direct air capture (DAC), continue to play a crucial role [151-154]. These methods also require further consideration before carbon capture from large, significant stationary sources is implemented. In fact, the atmospheric CO2 content is relatively low, making the DAC process much more energy-intensive. In light of this, it is critical to adopt a sustainable energy source option to ensure it can contribute to achieving net-zero or negative emissions. Thus, by combining CO_2 capture technology with renewable energy sources, it may be possible to reach neutral or negative emission goals (Table 6) [155-157].

Table 6 Integration of CO_2 Removal with Renewable Energy examples.

CO_2 Removal - Renewable Energy	Key Findings	References
Direct Air Capture (DAC) powered by Solar Energy	The process's carbon footprint can be reduced and its sustainability improved by powering direct air capture systems with solar energy.	[158]
Bioenergy with Carbon Capture and Storage (BECCS)	BECCS combines bioenergy production with carbon capture and storage, offering a way to remove CO_2 from the atmosphere while generating energy.	[29]
Wind-Powered Carbon Capture and Utilization	Utilizing wind energy to power carbon capture and utilization processes can create a sustainable cycle of energy generation and CO_2 removal.	[159]
Hydrogen Production from Renewable Sources with Carbon Capture	Producing hydrogen from renewable sources and capturing the associated CO_2 emissions can contribute to decarbonizing industrial processes.	[160]

The primary disadvantages of renewable energy sources are their low power density and intermittent supply [161]. Power generation methods that combine renewable energy sources with more traditional methods hold greater potential for effectiveness, especially when considering the dual objectives of increasing the proportion of renewable energy and decreasing carbon emissions [162]. By incorporating renewable energy alternatives into CO_2 capture technologies, the adverse effects of energy penalties may be alleviated, and the capture process's sustainability may be improved. Renewable energy sources have the potential to provide a direct energy supply for CO_2 capture processes, thereby partially mitigating the energy demand incurred by power plants for such processes [163]. Various renewable energy sources can be combined with CO2 capture technologies like thermochemical, electrochemical, photochemical, thermophysical, and biological methods. These technologies are still developing, each with distinct advantages and limitations. This research focuses on select review articles that summarize recent integration options [164]. While many carbon capture methods are well-known, this article primarily lists these technologies and examines renewable integration pathways in more detail. Space constraints prevent covering every published study, but interested readers can explore the listed publications and related technologies [164]. Calcium looping, a notable CO2 capture process, is explored for solar energy integration, featuring high operating temperatures (650-670°C for carbonation and 850-950°C for calcination) and requiring external energy due to its endothermic nature (178 kJ/mol) [165]. Previous studies have explored the integration of solar energy for carbon capture and storage [166, 167]. Strategies for incorporating renewable energy into CO2 capture technologies are lacking, often focusing on solar power with coal-fired plants. As CO2 emissions targets extend to hard-to-control sectors, such as heavy industry and transportation, innovative methods for integrating renewable energy are needed [168]. Negative emission solutions, such as Direct Air Capture (DAC), are crucial for approaching net-zero goals [164]. While solar thermal carbon capture has been widely studied [163, 169, 170], most reviews focus on coal-fired plants, neglecting other renewable options. Effective and affordable integration methods are essential for sustainability and public acceptance. Fluidized beds offer improved efficiency over wet slurry columns but require high temperatures and pressures for optimal conversion. Operating them with damp mineral particles at moderate temperatures combines the benefits of both systems [164]. Cohen et al. (2010) assessed the feasibility and impacts of using solar energy for CO2 capture [171]. Parvareh et al. [163] explored various configurations to integrate solar thermal energy with power plants implementing post-combustion capture (PCC), including: (1) generating steam with solar thermal energy for the PCC reboiler; (2) using solar energy to heat feed water or produce high-pressure steam for the turbine or boiler; and (3) integrating solar thermal energy with a retrofitted PCC power plant to supply the PCC reboiler with steam [164]. Manaf et al. (2016) extensively examined the modeling, design, and optimization of integrating a solar-thermal plant with a PCC-retrofitted power plant to minimize CO_2 capture costs [172].

7.ECONOMIC AND POLICY FRAMEWORKS IN CO_2 REDUCTION

Multiple researchers have identified a growing recognition among regions in the Eurozone and globally regarding the significance of international trade in advancing sustainable power and structural reforms [173]. Consequently, there has been an upsurge in the adoption of renewable energy sources in Asia and other parts of the world. The implementation of financial resources in an economic manner has resulted in numerous benefits for resource efficiency. Monetary authorities will have a substantial impact on combating climate change and promoting non-polluting energy sources such as wind power. Entrepreneurial portfolios should include ecological investments in order to mitigate the effects of pollution and global warming. Diverse methods in which climate risk may impact investment decisions are possible. Green trading strategies include alternative solution consumer lending, investment in renewable energy facilities (e.g., via project finance), and venture funding in renewable technology [174]. These strategies incorporate both synergistic and antagonistic screening mechanisms. However, the parameters governing specific financial enterprises and the requirements for environmentally sustainable investments remain ambiguous. Utilizing the term "climate policy" to overstate the actual impact of their company on the environment is an improper application of the term "collateralized debt obligations." The primary accountability for the environmental monitoring and reporting of an organization typically rests with financial institutions and issuers [175]. The environmental impacts of various government creditors are unreliable due to potential inherent conflicts of interest among lenders, purchasers, and specific objective providers. Transparency and consistency of indications are critical for investors and rating agencies in order to direct investment opportunities towards debtors who possess the capability to successfully implement the transition to a low-carbon economy. Conversely, some academics hold the view that economic integration facilitates the attainment of carbon neutrality to the maximum degree feasible. Financial integration, in their view, allows companies to more effectively monitor their environmental impact and adopt cutting-edge low-carbon technologies [176, 177]. As an approximation for inclusive funding, consider how economic development affects the ecological degradation of the top 15 polluters. This indicates that carbon dioxide emissions and economic development are negatively correlated. Technical innovation that alleviates energy poverty and reduces carbon dioxide emissions might help bring about a decrease in carbon emissions by way of financial integration. In their investigation into the impact of economic integration on energy poverty alleviation in Ghana [178], they found that enhancing the nation's financial integration could potentially result in the eradication of energy poverty. There is evidence linking energy poverty to the greenhouse gas impact as reported by Chien et al. [179], John and Deinde [180], and Zhao et al. [181-183], who also reported identical findings to ours. Economic integration can help nations minimize their carbon footprint by reducing energy poverty. In addition to the aforementioned linear relationship, financial inclusion and the greenhouse effect might also exhibit a nonlinear correlation. In their study, Weimin et al. [184] utilized the environmental Kuznets curve (EKC) to investigate the presence of an inverted U-shaped correlation between global carbon emissions and economic integration. To put it simply, economic integration and carbon dioxide emissions in China have an opposite relationship. Additional research by Yin et al. [185] has provided support for this conclusion. Nevertheless, the impact of economic integration on carbon emission reductions in the space sector, specifically in China, is often underestimated in academic research. Limited research, especially in China, has been devoted to examining the carbon ramifications of financial integration. In addition, numerous specialists in the field fail to consider this particular CO_2 collection method. The China Comprehensive Financial Consolidation Index examines the impact of financial consolidation on carbon emissions across various regions of the country by utilizing gender-specific tabular data spanning the years 2004 to 2018. Subsequent investigations will additionally center on the impact of energy efficiency fluctuations on the correlation between carbon emissions and economic inclusion. Policymakers will now be motivated to implement modifications to the current energy consumption pattern in response to the increasing energy demand paradigm. Nevertheless, the economic growth pattern, which is primarily driven by fossil fuel-based energy consumption, may be adversely affected by any abrupt or overnight changes in the energy consumption pattern. Consequently, policymakers may implement a phased energy transformation strategy that facilitates the transformation of energy consumption patterns without negatively impacting economic growth. Sectors with a higher price elasticity of demand for crude oil should be prioritized for substitution with crude oil during the initial phase. These sectors may be provided with renewable energy solutions at a pro-rata rate from the government, with a specific interest rate holiday period. This would allow the firms to bear the implementation cost of these solutions without any significant impact on their revenue stream. During this phase, the government will incur specific fiscal losses due to the interest rate holiday mechanism. Nevertheless, these losses can be progressively recouped during the second phase. Sectors with a reduced-price elasticity of demand for crude oil and fossil fuel-based energy should be prioritized during the second phase. In order to provide solutions for firms operating in these sectors, policymakers should implement a differential pricing mechanism. The price differential should be determined by the carbon footprint of the firms. This differential pricing mechanism can be interpreted as a Pigouvian Taxation mechanism, which is designed to internalize the negative environmental externalities that these sectors emit [186]. Here is a summary of previous research on economic and policy frameworks for CO_2 reduction, organized in Table 7.

Table 7 Previous Research on Economic and Policy Frameworks for CO_2 Reduction.

Research Topic	Key Findings	References
Carbon Pricing Mechanisms	Carbon taxes and cap-and-trade systems can effectively incentivize emission reductions and promote clean technologies.	[187]
Renewable Energy Subsidies and Incentives	Financial incentives such as feed-in tariffs can significantly promote the adoption of renewable energy sources.	[188]
Energy Efficiency Standards and Regulations	Energy efficiency standards and building codes play a crucial role in reducing energy consumption and CO_2 emissions.	[189]
Technological Innovation and Research Funding	Government funding and research grants contribute to the development and deployment of low-carbon technologies.	[190]
International agreements and Cooperation	International agreements such as the Paris Agreement facilitate global coordination on CO_2 reduction efforts.	[191]

8.CHALLENGES AND ISSUES

Carbon dioxide removal (CDR) and carbon dioxide utilization (CDU) are two critical approaches in addressing climate change and reducing greenhouse gas emissions. However, both face significant challenges related to cost, scalability, and technological barriers.

8.1.Cost Challenges

8.1.1.High Initial Investment

Technologies such as Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) require substantial upfront capital investment for infrastructure, equipment, and facilities. In addition, processes like converting CO2 into fuels, chemicals, or materials involve costly catalysts, high-energy inputs, and sophisticated processing equipment.

8.1.2.Operational Costs

The continuous operation of Carbon Dioxide Removal (CDR) technologies requires substantial energy input, particularly for Direct Air Capture (DAC) systems, which must filter and extract CO2 from ambient air. DAC processes, such as chemical absorption or adsorption, are especially energy-intensive due to the low concentration of CO2 in the atmosphere (approximately 0.04%). This low concentration necessitates the processing of large volumes of air, leading to high electricity consumption and operational costs, including significant expenses related to the compression and regeneration of sorbents or solvents used in the capture process [192, 193]. Furthermore, the utilization of captured CO2, whether for chemical synthesis, enhanced oil recovery, or mineralization, typically involves energy-intensive reactions. These reactions often require high temperatures and pressures, further contributing to the overall energy demand and increasing operational costs [194]. For instance, converting CO2 into fuels or chemicals through catalytic processes demands not only energy but also the continuous supply of raw materials, catalysts, and other reagents, all of which add to the economic burden. In addition to energy costs, maintenance of CDR systems can be a significant financial drain. Components such as filters, membranes, and reactors require regular maintenance and replacement, further driving up operational expenses. The need for a continuous supply of raw materials, including water and specific chemicals for processes like aqueous carbonation or electrochemical reduction, imposes additional financial challenges. Moreover, the procurement and disposal of catalysts and other consumables are critical aspects that can substantially influence the cost-effectiveness of these technologies [195, 196].

8.1.3.Economic Viability

The economic viability of carbon capture, utilization, and storage (CCUS) technologies is a critical concern in the global effort to mitigate climate change. Currently, the market price for carbon credits—typically ranging between $20 to $50 per ton of CO_2—often falls short of covering the full cost of capturing and storing CO_2, which can range from $50 to $150 per ton, depending on the technology and scale of deployment. This discrepancy makes it challenging for companies to justify large-scale investments in CCUS technologies without substantial financial incentives from governments, such as subsidies, tax credits, or more robust carbon pricing mechanisms. Moreover, the economic feasibility of products derived from CO_2 utilization hinges on their ability to compete with products made through conventional methods. For instance, producing synthetic fuels or chemicals from CO_2 is generally more expensive than producing the same products from fossil fuels. This is due to the high energy requirements and complex processes involved in converting CO_2 into valuable products. As a result, these CO_2-derived products often face significant market barriers unless there is strong regulatory support or a shift in market dynamics that favors low-carbon alternatives. To address these economic challenges, a combination of policy measures and technological advancements is essential. Governments can play a crucial role by implementing carbon pricing strategies that accurately reflect the social cost of carbon emissions, thereby incentivizing companies to invest in CCUS technologies. Additionally, continued research and development can help reduce the costs associated with CO_2 capture and utilization, making these technologies more competitive in the long term [197-201].

8.2. Scalability Issues

Scaling up carbon dioxide (CO_2) capture, utilization, and storage (CCUS) operations necessitates the development of extensive infrastructure, encompassing not only the technology for capturing CO_2 but also the systems required for its transportation and secure long-term storage. The infrastructure challenge is significant, involving the construction of pipelines that can transport CO_2 from capture sites to storage locations, which are often geologically secure underground reservoirs. These pipelines must be designed to handle large volumes of CO_2 under high pressure, ensuring safety and efficiency across potentially vast distances. Additionally, identifying and developing secure geological storage sites, such as depleted oil and gas fields or deep saline aquifers, is crucial. These sites must undergo rigorous evaluation to ensure their capacity to store CO_2 over long timescales without leakage, which is a significant technical and regulatory hurdle. Large-scale utilization of CO_2 further complicates the scaling process, as it requires extensive manufacturing and processing facilities capable of handling and converting significant volumes of CO_2 into valuable products. These facilities must be designed to operate at an industrial scale, which can be logistically challenging due to the need for consistent CO_2 supply, raw materials, and energy. The energy required to capture and store CO_2 at scale is immense, often leading to concerns about the sustainability of such efforts. The energy intensity of CO_2 capture, particularly when employing technologies like chemical absorption, is high, necessitating the development of energy-efficient processes and the integration of renewable energy sources. If the energy used in CCUS operations comes from fossil fuels, the process risks becoming counterproductive, as the emissions generated could offset the benefits of CO_2 capture. To address the increased energy demands of scaling up CO_2 utilization processes, it is imperative to identify and implement sustainable and cost-effective energy sources. Renewable energy sources such as solar, wind, and geothermal power offer promising alternatives, but integrating these into CCUS operations on a large scale presents challenges related to the variability, storage, and distribution of energy. Moreover, the transition to renewable energy must be carefully managed to avoid unintended emissions that could undermine the climate benefits of CO_2 capture and utilization. This dual challenge of energy demand and sustainability highlights the need for continued innovation in both CO_2 capture technologies and energy systems, as well as supportive policies and incentives to drive the adoption of low-carbon solutions at scale. Addressing these challenges is critical for the successful deployment of CCUS as a key strategy in mitigating climate change, as highlighted by various studies and industry reports [110, 197].

8.3. Technological Barriers

8.3.1. Technological Barriers: Efficiency, Performance, Storage, and Longevity

Improving the efficiency of CO_2 capture technologies to capture more CO_2 per unit of energy consumed is crucial. Current technologies often have limitations in terms of capture rates and energy efficiency. In addition, developing catalysts and processes that efficiently convert CO_2 into valuable products remains an ongoing challenge. Current technologies often face limitations in terms of conversion rates and selectivity. Ensuring that captured CO_2 can be stored securely and for long durations without leakage is a significant technological challenge. Advanced monitoring and verification technologies are needed to ensure the integrity of storage sites. Additionally, developing stable and durable products from CO_2 utilization that can store carbon for extended periods without releasing it back into the atmosphere is essential. Decarbonization via CDUS represents a potentially effective avenue for the amelioration of climate change. Notwithstanding this, in order to optimize the efficacy and viability of these technologies, a number of obstacles and prospects must be considered. A significant obstacle is the exorbitant expense linked to CCS technologies (Figure 8). Due to the combination of substantial infrastructure requirements, high energy and capital demands, and economic impracticability, these technologies may be unsuitable for a variety of industries [202-204]. Moreover, there is still a lack of comprehensive understanding regarding the long-term stability of CO_2 storage sites, which presents a potential risk of leakage and consequent damage to the environment [205-207].

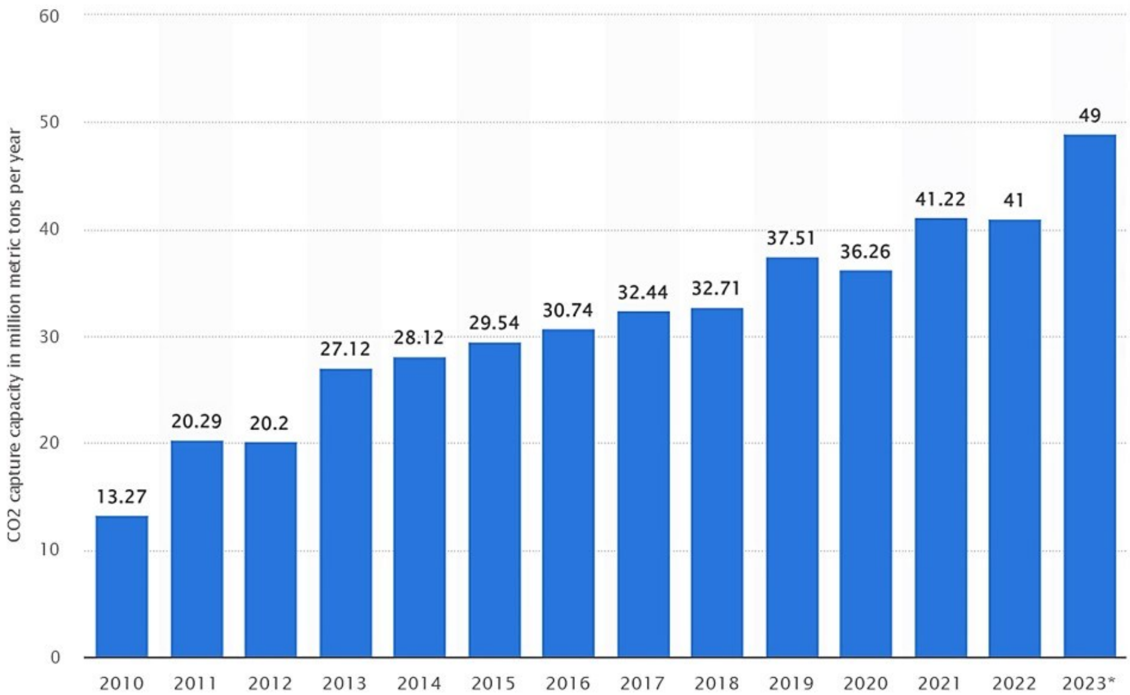

Fig. 8 Capture Capacity of Operational Commercial Carbon Capture and Storage (CCS) Facilities Worldwide from 2010 to 2023 [208].

An additional obstacle that must be addressed is the scarcity of appropriate CO_2 storage locations in specific areas [209, 210]. For instance, regions characterized by dense populations or restricted land resources might lack the geological formations essential for the efficient storage of CO_2 [211]. Implementing CCS technologies also necessitates substantial regulatory and policy support, in addition to public acceptability, which can be challenging to attain [156, 204, 212]. However, numerous opportunities are also presented by the CDUS (Figure 9). The progression and integration of these technologies possess the capacity to incentivize inventive thinking, facilitate the establishment of fresh sectors, and produce employment opportunities [213, 214]. The utilization of CO_2 in the production of valuable goods may also contribute to the development of a more sustainable and circular economy [215-217]. In addition, the adoption of CCS technologies can facilitate the reduction of global emissions targets and aid in mitigating the environmental impact of fossil fuel consumption [156, 218]. In order to maximize the capabilities of these technologies, it is imperative to thoroughly evaluate the opportunities and challenges that are linked to decarbonization via CDUS. Ongoing investigation and advancement, in addition to policy and regulatory support, are imperative in order to surmount the obstacles and completely realize the advantages of these methodologies. The thermodynamic stability of C=O bonds and the rapid deactivation of catalysts continue to pose an open challenge for the majority of CO_2 transformation technologies in achieving high CO_2 conversion. The processes operate under high temperatures/pressures, or with excess overpotentials, or using catalysts with low availability and high costs (e.g., noble metals and ionic liquids), despite the fact that good conversion efficiencies are reported (≥60%) for reforming, hydrogenation, carboxylation, and electrochemical technologies. As a result, additional research is necessary to identify new catalysts that exhibit enhanced stability and activity while operating at reduced costs and under more favorable operational conditions. It is also necessary to clarify the mechanisms of CO_2 activation and/or electron transfer during CO_2 conversion processes, particularly for plasma catalysis, photochemical reduction, non-photosynthetic, and electrochemical reduction, in order to identify and control the various steps in elementary reactions, thereby overcoming the limitations of CO_2 conversion [219]. Table 8 below summarizes most of the challenges and opportunities.

Table 8 Most Challenges and Opportunities

Topic	Challenges	Opportunities	References
Technological Advances	High costs and energy requirements for CO_2 removal methods. Lack of scalability for some technologies.	Research and development to improve efficiency and reduce costs. Collaboration with industries for innovation.	[158, 220]
Policy and Regulation	Limited policies and incentives to support CO_2 removal. Lack of international cooperation on carbon reduction.	Advocacy for government support and implementation of carbon removal policies. International agreements for carbon reduction.	[221-223]
Public Awareness	Limited public understanding of CO_2 removal technologies. Skepticism and resistance to new environmental approaches.	Education and awareness campaigns to inform the public about the importance of CO_2 removal. Engagement with communities to build support.	[224, 225]
Environmental Impact	Potential environmental risks associated with CO_2 removal methods, such as land use and mineral extraction.	Sustainable practices and monitoring to minimize environmental impact. Integration of CO_2 removal with ecosystem restoration efforts.	[29, 226]
Economic Viability	Uncertain business models and market demand for CO_2 removal. Limited financial incentives for investment.	Development of carbon markets and financial mechanisms to create demand for CO_2 removal. Integration of carbon removal with corporate sustainability goals.	[227-229]

9.CASE STUDIES OF SUCCESSFUL CO2 REMOVAL IMPLEMENTATIONS

Petra Nova – United States: Texas, USA, is home to the CCS project Petra Nova. It can remove as much as 90% of carbon dioxide gas from a coal-fired power station's emissions by employing post-combustion carbon capture technology. Improved oil recovery is achieved by injecting the collected CO_2 into oil fields via a pipeline. With this initiative, we can sequester up to 1.6 million tonnes of carbon dioxide equivalent per year [230]. Sleipner – Norway: The Sleipner project, situated in the North Sea, is the initial offshore CCS project in the world. The procedure involves injecting captured CO2 from the processing of natural gas into a deep salt aquifer for long-term storage. With an annual capacity of up to 1 million tonnes of CO_2, the project has been operational since 1996 [231]. Canada. An annual capacity of one million tonnes of CO_2 is captured through the utilization of post-combustion carbon capture technology at a bitumen upgrader facility. Following pipeline conveyance, the captured CO_2 is injected for storage into a deep saline aquifer. Effective as of 2015, the project has been operational [232]. Germany – Ketzin: The Ketzin initiative was a carbon capture and storage (CCS) pilot project in Germany. Carbon dioxide was pumped into a saltwater aquifer for the purpose of storage. From 2008 to 2013, the program was operational, and it stored up to 67,000 metric tons of carbon dioxide [233].

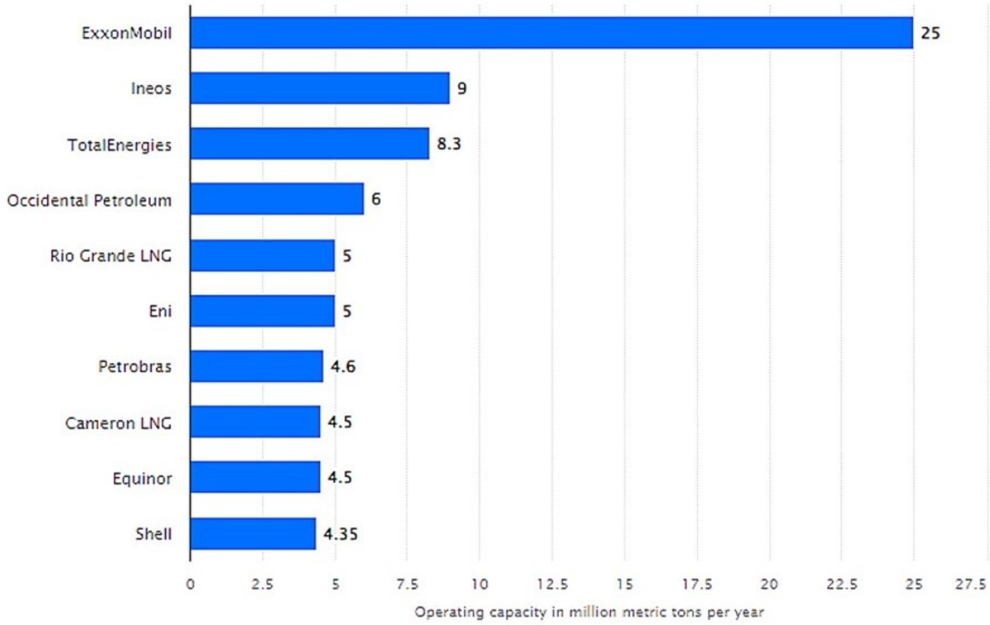

Fig. 9 Leading Carbon Capture, Use, and Storage (CDUS) Companies Worldwide in 2020, by Operating Capacity (in Million Metric Tons of CO_2 Per Year) [234].

Carbfix – Iceland: Iceland is home to the carbon-capturing and storing project known as Carbfix. Mineralization is the method by which CO_2 is captured and stored. Subterranean basaltic rock formations are injected with a mixture of captured CO_2 and water, where it undergoes a chemical reaction with minerals to generate steady carbonates. The annual storage capacity of the facility is 4 million tonnes of CO_2 [235]. Carbon Engineering – Canada: Carbon Engineering is a for-profit DAC that has been around since 2009 and counts Bill Gates & Murray Edwards among its backers. It is possible to extract about one tonne of carbon dioxide (CO_2) per day from a pilot facility in British Columbia, Canada, which has been running since 2015. According to economic research conducted between 2015 and 2018, the cost of removing CO_2 were \$94–232 per metric ton. It uses a solution of potassium hydroxide to react with CO2, creating potassium carbonate, and then works in tandem with Greyrock to convert concentrated CO_2 into synthetic fuels [236]. Climeworks – Switzerland: Since May 2017, Climeworks has maintained a DAC plant of industrial scale in Hinwil, Switzerland, where it annually captures 900 tonnes of carbon dioxide. Through the use of heat generated by a nearby trash incineration plant, the facility increases harvests from surrounding greenhouses of vegetables and decreases energy consumption. Capturing one kilogram of CO_2 requires approximately \$600. Climeworks and Reykjavik Energy have formed a partnership for the Carbfix project in Hellisheidi, Iceland, which mineralizes CO_2 injected deep underground into basaltic bedrock in conjunction with a geothermal power facility [236]. Global Thermostat, a privately held organization established in 2010, located in New York, United States, eliminates dissolved CO_2 from the atmosphere via carbon substrates coated with amine-based sorbents. Their capacity for annual initiatives ranges from 40 to 50,000 tonnes, and their Huntsville facility is reportedly operating at a cost of \$120 per tonne. Global Thermostat has formed partnerships with a gasoline business headquartered in DAC, including ExxonMobil and Coca-Cola, for the procurement of CO_2 for beverages [236]. Soletair Power – Finland: A firm called Soletair Power was founded in 2016. It uses DAC to improve indoor air quality by removing CO_2 from buildings. For every 400 ppm of CO2 eliminated, cognitive performance may be improved by 20%. An industrial base material and a synthetic renewable fuel are both made from captured CO_2. In order to create synthetic methane from buildings' collected carbon dioxide, A Powerto-X demonstration unit was developed in collaboration with Wartsila and Q Power in preparation for the 2020 Dubai Expo [236]. Prometheus Fuels – Santa Cruz, United States: Prometheus Fuels, a 2019 startup based in Santa Cruz, California, United States, specializes in DAC technology for the conversion of atmospheric CO_2 into aviation fuel and petrol with zero net carbon emissions. Electrocatalysis is employed to convert carbon dioxide into alcohols, which are subsequently processed through carbon nanotube membranes to produce fuels. The procedure makes sole use of renewable electricity, culminating in the combustion of fuels that are carbon-neutral [236]. The first commercial facility to utilize Blue Planet Systems' patent-protected carbon mineralization process is currently being planned and constructed by San Francisco Bay Aggregates. The plant will permanently deposit CO_2 in synthetic limestone aggregate through mineralization, which will be collected from the adjacent Los Medanos Energy Center. SF Bay Aggregates is at the vanguard of the development of this paradigm-shifting technology and will supply carbon-negative aggregate to Bay Area projects by 2022 [237]. A temporary departure area was constructed at San Francisco International Airport using Blue Planet technology. MC and Blue Planet will conduct a feasibility study on the prospective use of the technology in Silicon Valley until the fiscal year 2021. Subsequently, the partners intend to make the technology commercially available [238]. A pilot initiative has been initiated by Blue Planet and Sulzer to reduce CO_2 emissions and reshape the cement industry into a sustainable one. Sulzer Chemtech, the industry leader in separation and mixing technology, is currently constructing an efficient and effective carbon capture unit at Blue Planet's pilot facility in Pittsburgh. This unit will enable the production of high-quality products when reacted with captured CO_2 [239]. Table 9 shows Comprehensive data, including the CO_2 capture capabilities of multiple companies.

Table 9 Detailed Information of Various Companies with CO_2 Capture Capacities and Operational Status [240].

Company	Project	Country	CC (tons of CO_2/ year)	Equivalent Annual Emissions of Passenger Vehicles	Technology
Occidental Petroleum	Permian Basin CCF	USA	90,00,000	1.9 million	Post-combustion
Air Products	Port Arthur CCS project	USA	10,00,000	213,000	Cryogenic distillation
Chevron	Gorgon Project	Australia	40,00,000	850,000	Pre-combustion
ExxonMobil	Gorgon Project LaBarge CCS project Sleipner Project	Australia USA Norway	10,00,000	213,000	Various
Total	Northern Lights project	France	50,00,000	1 million	Post-combustion
Equinor	Sleipner Project Northern Lights project	Norway	50,00,000	1 million	Post-combustion
Shell	Quest project	Canada	10,00,000	213,000	Post-combustion
Mitsubishi Heavy Industries	Petra Nova project	Japan	16,00,000	341,000	Post-combustion
Carbon Clean Solutions	Multiple projects	India	10,00,000	N/A	Various
SaskPower	Boundary DamCarbonCapture and Storage project	Canada	10,00,000	213,000	Post-combustion
Carbon Engineering	Pilot Plant	Canada	~365	~80 passenger vehicles	DAC with potassium hydroxide solution
Climeworks	DAC Plant	Switzerl	900	~197 passenger vehicles	DAC with waste heat utilization
Global Thermostat	Various Projects	USA	40–50,000	Varies	DAC with amine-based sorbents and carbon sponges

10.FUTURE PROSPECTS AND EMERGING TECHNOLOGIES

We are optimistic about CDUS's future. From 2021 to 2026, the worldwide market for capturing and storing CO_2 is projected to rise at a CAGR of 11.7%, reaching $6.9 billion by 2026. The main factors propelling this expansion are stricter government rules and policies aimed at reducing greenhouse gas emissions [241, 242]. The CDUS is also anticipated to become more efficient and cost-effective as a result of technological improvements. An essential part of studying how to use CO_2 is coming up with innovative ways to transform it into useful products, such as fuels, chemicals, and construction materials. The possibility of employing carbon dioxide (CO_2) as a feedstock in the generation of renewable energy is also the subject of ongoing research [243, 244]. As an example, carbon dioxide can be utilized as a starting material for the cultivation of microbes or algae that produce biofuels [245]. Research into CO_2 sequestration is currently focused on improving the dependability and security of geological storage sites and investigating alternative sequestration technologies, such as ocean storage and mineralization. Ionic liquids and metal-organic frameworks are examples of emerging materials and technologies that are showing promise for CO_2 capture in the future [246-250]. While CDUS has many obstacles, the future is bright. Establishing legal frameworks to guarantee the efficacy and safety of CO_2 storage sites is essential, as is the public's support for and substantial investment in large-scale initiatives. Additional methods and technologies must be created in order to improve the cost-effectiveness and efficacy of CDUS [236]. Ongoing CDUS research has a key emphasis on improving capture technology. Many existing capture technologies, specifically, capture after combustion systems, incur high energy costs, which can reduce the general effectiveness of power stations and manufacturing operations. A significant number of scholars are aiming for more efficient and less expensive capture methods. We aim to increase the rates of CO_2 capture while decreasing the energy requirements of these operations. In this respect, promising new technologies have emerged, such as cryogenic separation and systems based on membranes. Potentially using less energy than conventional absorption methods, membrane-based systems isolate CO_2 from other gases through the use of selective membranes. In order to efficiently extract CO_2, cryogenic separation requires lowering gases to very low temperatures. Both the performance and the price of CDUS systems could be improved by these developments, which would make them more attractive for large-scale deployment [236].

11.CONCLUSIONS

The present article offers a thorough examination of the most recent scientific developments, modification strategies, and the maturation, cost, market, and CO_2 consumption of a variety of technologies. Furthermore, it offers a comprehensive examination of research trends and global CO_2 utilization initiatives. Lastly, the challenges and prospective research directions are addressed. The following points summarize the essential findings and emphasize the main trends of CO_2 technologies:

1- It is essential to develop a diverse array of mitigation and adaptation strategies that consider the current climate situation in order to achieve the 1.5 ◦C targets by the end of the century.

2- The potential of mineral carbonation technologies in the short term is particularly promising, particularly in the context of concrete building materials. The primary reason for this is the significant and continuous demand for concrete, as well as the combined advantage of enhancing material strength while sequestering CO_2 for an extended period. The primary goal of enhanced oil recovery is not the permanent storage of CO2, and it is driven by the desire to minimize costs by utilizing naturally sourced CO2. As a result, it may be perceived as less exhilarating. It is uncertain whether it is feasible to expand the CO2 storage capacity of enhanced oil recovery sequestration sites to their maximum capacity in the near future, despite their immense capacity for CO_2.

3- The prepared review indicates that the preponderance of the commercial, large-scale CDUS facilities that are currently operational are associated with natural gas processing and utilize CO_2.

4- Further research and development are required to identify innovative methods for CO_2 removal and to improve the efficacy and affordability of current approaches. In order to achieve significant reductions in atmospheric CO_2 levels and mitigate climate change, it may be necessary to implement a diverse array of CO_2 removal technologies and strategies.

5- The implementation of carbon capture on a large scale is untenable due to its prohibitively expensive development. The implementation of carbon pricing mechanisms, such as a cap-and-trade system or a carbon levy, could serve as a financial incentive for companies to invest in these technologies. At present, the market does not entirely recognize the advantages of removing CO_2 from the atmosphere. The cost of fossil fuels remains low, and there is a dearth of robust economic incentives for the development and deployment of CO_2 removal technologies.

6- The competitiveness of CO_2 removal technologies can be enhanced through policy interventions, such as carbon pricing mechanisms. By increasing the cost of fossil fuels and encouraging the development of healthier technologies, they can create a level playing field. The free market cannot solely drive the adoption of CO2 removal technologies. In order to expedite the development and deployment of these technologies, we require financial incentives and policy support.

Overall, the development and deployment of CO_2 removal technologies are essential for addressing climate change and transitioning to a sustainable future. Therefore, policy support and financial incentives are crucial. Governments can harness the potential of these technologies and establish a more sustainable and cleaner world by establishing the appropriate conditions. In general, there is a significant interest in carbon capture, whether for storage or utilization, and research efforts are gaining momentum.

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