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Carbon Capture and Utilisation: A narrative review on Chemistry and Practical Limits

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ABSTRACT

Carbon capture and utilisation (CCU) is often presented as a way to turn carbon dioxide from a waste into a resource. This narrative review examines the chemistry behind capture and conversion and the practical limits that determine how much CCU can contribute. Global fossil CO_2 emissions reached about 38.1 Gt in 2025, whereas operating capture facilities handled about 64 Mt per year in mid-2025 and all CO_2 used industrially, mainly for urea and enhanced oil recovery, is about 230 Mt per year. Capture chemistry is mature for concentrated and moderately dilute streams: amine scrubbing forms carbamates that are reversed by heating, while direct air capture of the 0.04% CO_2 in air uses an aqueous KOH and calcium loop at estimated costs of US$ 94–232 per tonne in one engineering analysis. Conversion is limited by the thermodynamic stability of CO_2: it needs a high-energy partner such as hydrogen, an epoxide or ammonia, or electricity. Stoichiometry shows the scale of that requirement, with 1.4 t of CO_2 and 0.19 t of hydrogen needed per tonne of methanol. Pathways differ greatly in maturity: urea and epoxide-derived polymers are commercial, CO_2 hydrogenation to methanol is advancing through catalyst development, and electroreduction would need about 60% energy efficiency and very cheap renewable electricity to compete. A major assessment found that utilisation pathways differ in scale, cost and permanence, and that polymers can be profitable while fuels sit high on the cost curve. Life-cycle assessment is essential, because utilised CO_2 is not automatically a negative emission. India has begun to frame a CCUS policy, with a 2022 NITI Aayog framework and a 2026–27 budget announcement of ₹20,000 crore. It is concluded that CCU is a niche contributor whose value depends on low-carbon energy, product permanence and displaced fossil carbon, and that it should complement, not replace, emission reduction.

Key words: Carbon capture; CO_2 utilisation; amine scrubbing; direct air capture; methanol; polycarbonates; electroreduction; life-cycle assessment; India.

1. Introduction

Global fossil CO_2 emissions are still rising: the Global Carbon Budget 2025 projected a record of about 38.1 Gt for the year [1]. Carbon capture, utilisation and storage (CCUS) is one of the tools proposed to cut emissions from sectors that are hard to decarbonise. The Global CCS Institute counted 77 operating capture facilities capturing about 64 Mt of CO_2 per year in mid-2025, with projects in the pipeline representing about 513 Mt per year [2]. Utilisation is much smaller than storage in climate terms: about 230 Mt of CO_2 is used each year, of which roughly 130 Mt goes into urea and 70–80 Mt into enhanced oil recovery [3] (Figure 1).

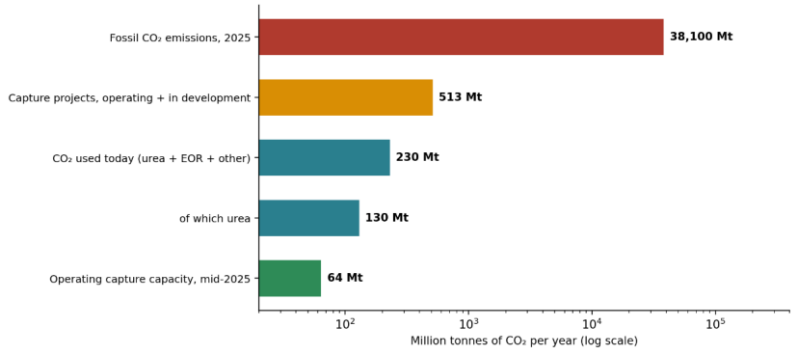

Figure 1. Scale of CO_2 flows. Fossil emissions [1]; capture projects operating and in development, and operating capacity [2]; CO_2 used industrially today, and urea [3]. Note the logarithmic scale. Graph prepared from published values.

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Utilisation, as distinct from storage, converts captured CO_2 into products. The idea is attractive, but chemistry and scale impose limits. This review explains the chemistry of capture and conversion, summarises the evidence on potential and cost, sets out the practical limits, and considers India's emerging policy. It is a narrative review: sources were selected by the author from major reviews, assessments and official reports, without a systematic search, and the field changes quickly.

2. Chemistry of Capture

2.1 Amine scrubbing

Amine scrubbing is the benchmark technology for capturing CO_2 from flue gas and has been used industrially for decades [4]. In an absorber, an aqueous amine reacts with CO_2 to form a carbamate and an ammonium ion (Figure 2A); in a stripper, heat reverses the reaction, releasing a concentrated CO_2 stream and regenerating the solvent. The thermodynamic minimum work to capture CO_2 from flue gas and compress it to 150 bar is about 0.11 MWh per tonne, and improvements in process and solvent have been proposed to bring practical requirements to about 0.2 MWh per tonne [4]. Real plants require much more energy than the minimum, which is the main reason for the cost of capture.

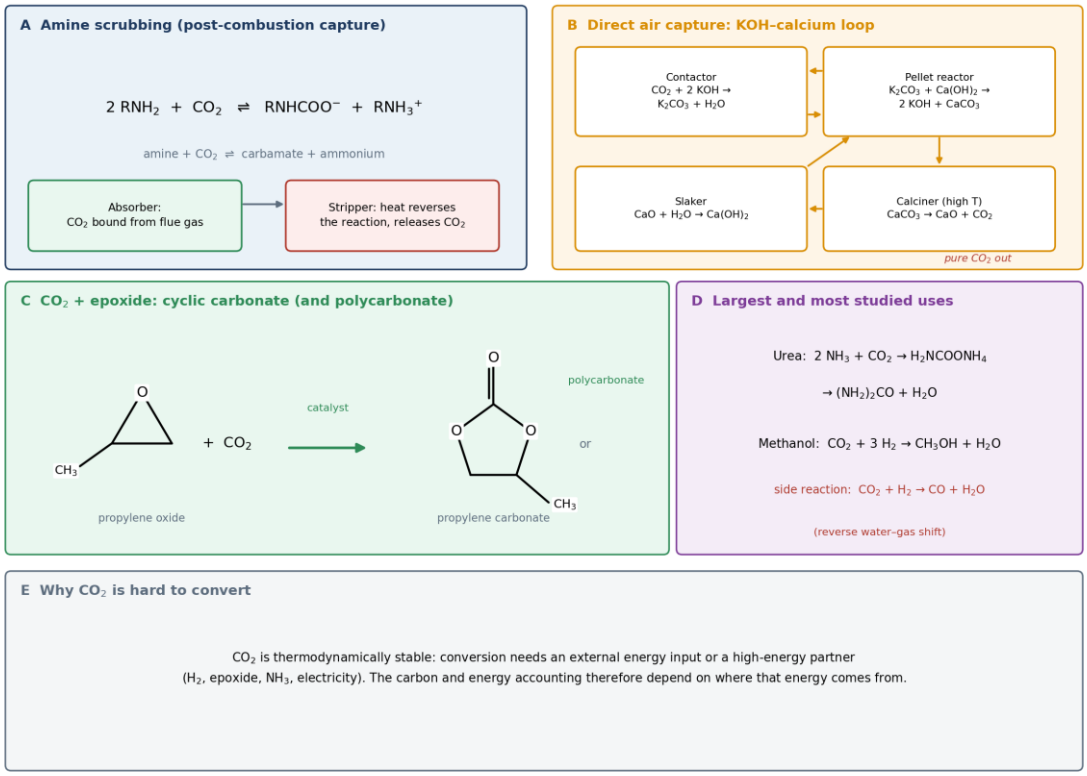

Figure 2. Chemistry of capture and conversion: (A). Amine scrubbing [4]; (B). Direct air capture with an aqueous KOH solution and calcium caustic recovery loop [5]; (C). CO_2 with an epoxide gives a cyclic carbonate or a polycarbonate depending on catalyst and conditions [6]; (D). Urea synthesis and CO_2 hydrogenation to methanol, with the competing reverse water-gas shift reaction [7,8]; and (E). The thermodynamic constraint [7].

2.2 Direct air capture

Air contains only about 0.04% CO_2, so direct air capture (DAC) must move very large volumes of air through a contactor. One engineering design uses an aqueous KOH solution to absorb CO_2 as potassium carbonate, followed by a calcium caustic recovery loop that precipitates $CaCO_3$ and regenerates the hydroxide, with calcination of $CaCO_3$ releasing pure CO_2 (Figure 2B). The analysis estimated an energy demand of 8.81 GJ of natural gas, or 5.25 GJ of gas plus 366 kWh of electricity, per tonne of CO_2, and a cost of US$94–232 per tonne depending on assumptions [5]. The dilute feed makes DAC far more energy intensive than point-source capture (Figure 3).

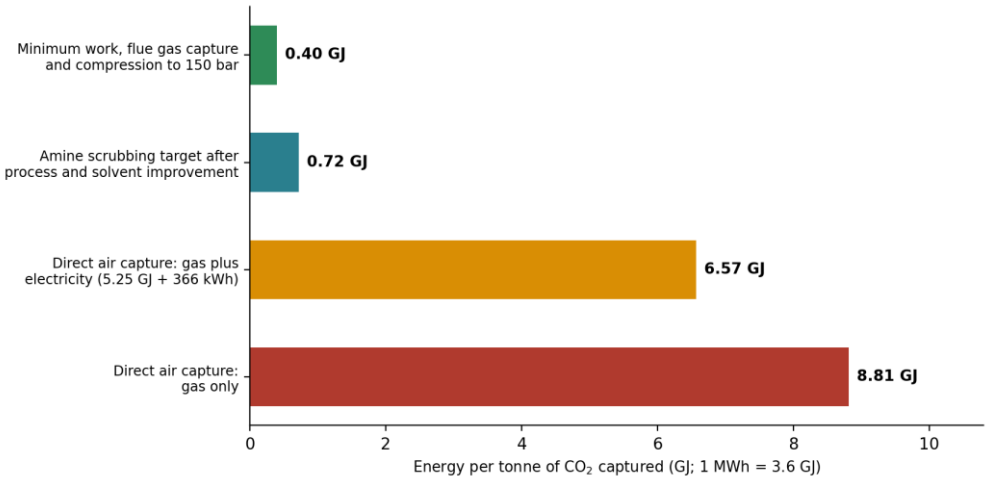

Figure 3. Energy for capture per tonne of CO_2. The first two bars are thermodynamic work and an improved amine process for flue gas [4]; the last two are an aqueous KOH direct air capture design [5]. Work and thermal energy are not strictly equivalent, so the comparison indicates magnitude only. Graph prepared from published values.

Table 1. Capture routes: Chemistry, status and limits.

Route	Chemistry	Status and numbers	Main limit	Ref.
Amine scrubbing	Amine + CO_2 ⇌ carbamate + ammonium; heat regenerates	Long industrial use; minimum work about 0.11 MWh/t, improved process about 0.2 MWh/t	Regeneration energy	[4]
Direct air capture (KOH–Ca loop)	CO_2 + 2 KOH → K_2CO_3; calcium loop regenerates KOH; calcination yields CO_2	8.81 GJ gas, or 5.25 GJ plus 366 kWh, per tonne; US$94–232/t	Energy and cost of dilute feed	[5]
Operating base	Mixed technologies	77 facilities, about 64 Mt/yr (mid-2025); pipeline about 513 Mt/yr	Scale vs 38.1 Gt emissions	[1,2]

3. Chemistry of Conversion

CO_2 is thermodynamically stable, so its conversion needs an external energy input or a high-energy reaction partner; the synthesis of urea from ammonia, in which a high-energy reagent drives the reaction, is a standard example [7]. This single constraint shapes every utilisation route (Figure 2E, Table 2).

3.1 Urea

Urea is the largest industrial use of CO_2, consuming about 130 Mt per year [3]. The reaction of two molecules of ammonia with CO_2 gives ammonium carbamate, which loses water to form urea (Figure 2D). By stoichiometry, 0.73 t of CO_2 is consumed per tonne of urea. Because urea is used as a fertiliser and the carbon is released when it is applied, this use stores carbon only briefly, and it depends on ammonia, whose production requires hydrogen.

3.2 Methanol by CO_2 hydrogenation

CO_2 can be hydrogenated to methanol ($CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$), which is a platform chemical and a candidate fuel. Heterogeneous catalysts based on copper and on indium oxide have been developed, and the field has been reviewed extensively [8]. The reaction competes with the reverse water–gas shift reaction that gives CO (Figure 2D), which limits selectivity and conversion per pass [8]. Stoichiometry shows that the hydrogen demand is large: 1.38 t of CO_2 and 0.19 t of H_2 per tonne of methanol (Figure 4). The climate benefit therefore depends on whether the hydrogen is produced with low-carbon energy.

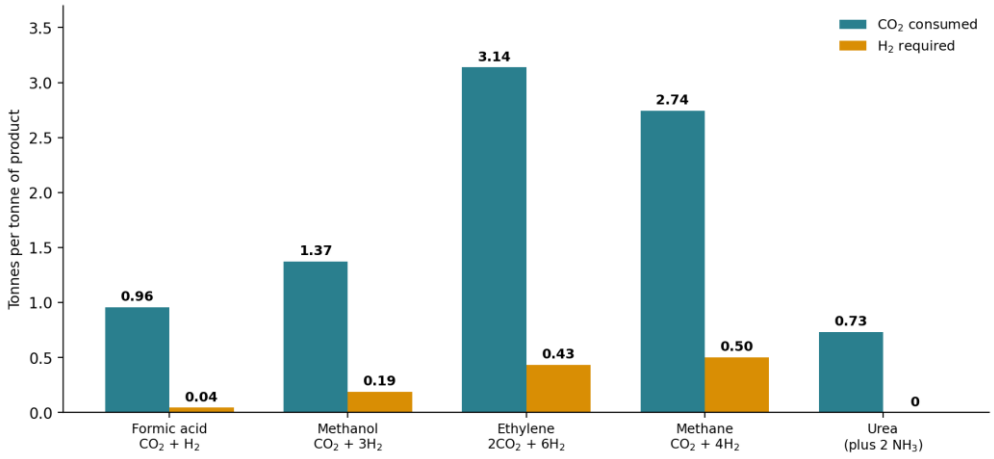

Figure 4. CO_2 consumed and hydrogen required per tonne of product, calculated by the author from reaction stoichiometry. Urea production also requires ammonia, whose production needs hydrogen.

3.3 Cyclic carbonates and polycarbonates

CO_2 reacts with epoxides, which are strained, high-energy reactants, to give cyclic carbonates or, with suitable metal catalysts, polycarbonates (Figure 2C). Discrete metal catalysts for this copolymerisation, and their mechanisms, have been reviewed [6]. In the assessment of utilisation pathways, polymers made with CO_2 are among those that can be profitable today, though the amount of CO_2 they can use is limited by the size of the polymer market [9].

3.4 Electrochemical reduction

Electroreduction of CO_2 to products such as CO, formate or ethylene uses electricity directly. A techno-economic analysis concluded that for renewably powered electrosynthesis to displace petrochemical processes, high energy efficiency (about 60% or more) and low-cost renewable electricity (below about 4 cents per kWh) would be required [10]. These conditions are demanding and explain why electroreduction is still at an earlier stage than urea or polymers.

Table 2. Utilisation routes: Reaction, status and limits.

Route	Reaction	Status	Main limit	Ref.
Urea	$2\ NH_3 + CO_2 \rightarrow$ urea + H_2O	About 130 Mt CO_2/yr; 0.73 t CO_2 per t urea	Carbon released on use; needs ammonia	[3,7]
Methanol	$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$	Cu and In_2O_3 catalysts under development	Hydrogen demand; reverse water–gas shift	[8]
Cyclic carbonates and polycarbonates	CO_2 + epoxide → carbonate or polymer	Metal catalysts; polymers can be profitable	Small market size	[6,9]
Electroreduction	$CO_2 + e^- + H^+ \rightarrow$ CO, formate, ethylene	Earlier stage	Needs about 60% efficiency and cheap power	[10]
Fuels and chemicals (general)	Hydrogenation and related routes	Fuels sit high on the cost curve	Energy and cost	[9]

4. Evidence on Potential and Climate Benefit

An influential assessment examined ten utilisation and removal pathways, including chemicals, fuels, microalgae, concrete building materials, forestry and biochar, and distinguished pathways that cycle carbon from those that remove it from the atmosphere. It found that pathways differ markedly in scale, cost and permanence: for example, polymers may be profitable now while fuels remain expensive, and construction materials can both use and hold CO_2 [9] (Figure 5).

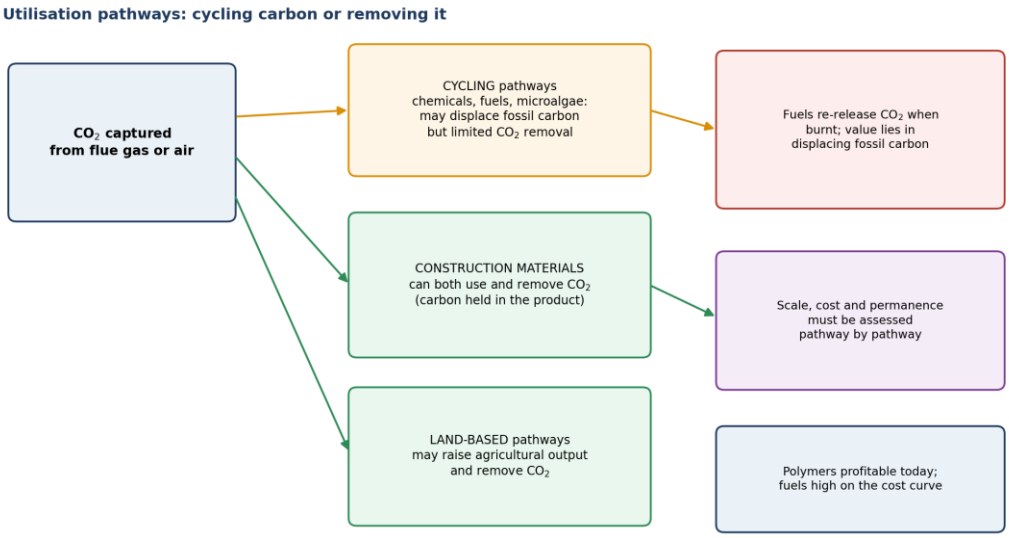

Figure 5. Utilisation pathways classified by whether they cycle or remove carbon, based on ref [9].

Whether CCU reduces emissions at all is a question for life-cycle assessment (LCA). Guidance on LCA for CO_2 capture and utilisation highlights common pitfalls, such as misleading system boundaries and treating utilised CO_2 as an avoided emission without accounting for energy inputs and what the product replaces [11,12]. This is why Figure 6 lists the questions to ask before a CCU benefit is claimed.

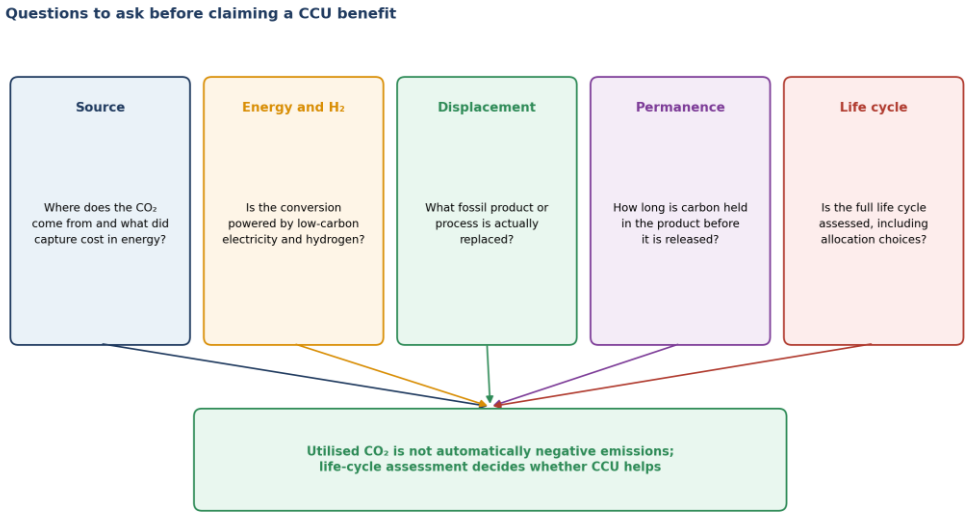

Figure 6. Questions to ask before claiming a climate benefit from CCU, based on refs [9,11,12].

5. Practical Limits

Four limits recur. First, scale: fossil emissions are about 38.1 Gt per year [1], whereas all current industrial CO_2 use is about 230 Mt [3] and capture capacity about 64 Mt [2], so even a large expansion of utilisation would address only a small fraction of emissions unless storage is also pursued. Second, energy: capture from dilute streams demands substantial energy [4,5], and conversion needs hydrogen or electricity, as the stoichiometry shows (Figure 4). Third, permanence: products such as fuels and urea release carbon quickly, whereas construction materials can hold it for longer [9]. Fourth, accounting: without LCA, claims about avoided emissions can be misleading [11,12]. Table 3 summarises the limits.

Table 3. Practical limits of CCU.

Limit	Evidence	Implication	Ref.
Scale	Fossil CO_2 38.1 Gt/yr vs about 230 Mt used and about 64 Mt captured	CCU cannot replace emission cuts or storage	[1–3]
Energy for capture	Minimum 0.11 MWh/t for flue gas; 5.25 GJ plus 366 kWh/t for DAC	Dilute sources cost most	[4,5]
Hydrogen and electricity	1.38 t CO_2 and 0.19 t H_2 per t methanol; electroreduction needs about 60% efficiency	Low-carbon energy is a prerequisite	[8,10]
Permanence	Cycling vs removing pathways	Short-lived products give limited removal	[9]
Accounting	Pitfalls in system boundaries and allocation	Use full LCA	[11,12]

6. India

In November 2022 NITI Aayog published a study on a CCUS policy framework and its deployment mechanism for India [13]. The Union Budget for 2026–27 announced an allocation of about ₹20,000 crore over five years for CCUS in sectors including power, steel, cement, refineries and chemicals [14]. For chemists, the immediate opportunities are catalyst and sorbent development, utilisation in polymers and building materials, and LCA studies that reflect Indian grid and hydrogen conditions, since the benefit of any utilisation route depends on the carbon intensity of the energy used [11]. Table 4 lists the main policy points.

Table 4. Indian policy markers for CCUS.

Instrument	Content	Date	Ref.
NITI Aayog CCUS report	Policy framework and deployment mechanism for CCUS in India	November 2022	[13]
Union Budget 2026–27	About ₹20,000 crore over five years for CCUS in power, steel, cement, refineries and chemicals	2026	[14]

7. Challenges

The main challenges are chemical, economic and conceptual. Chemically, the thermodynamic stability of CO_2 means every route needs an energy source, and catalysts must cope with competing reactions such as the reverse water–gas shift [7,8]. Economically, capture is energy intensive and DAC costs remain high [5], and utilisation markets other than polymers are limited [9]. Conceptually, CCU is easily oversold: using CO_2 does not by itself mean it has been removed from the atmosphere, and LCA is needed to show net benefit [11].

8. Future Directions

Priorities include lower-energy capture chemistries and sorbents, and better catalysts for hydrogenation and electroreduction that raise selectivity and efficiency [8,10]. Utilisation in products that hold carbon for long periods, such as construction materials, deserves attention [9]. Standardised LCA methods should be applied to every CCU claim [12]. For India, pilot projects linked to low-carbon electricity and hydrogen, and Indian-specific LCA, would show where CCU makes sense [13,14]. CCU should be developed alongside, and not instead of, emission reduction and geological storage.

9. Conclusions

The chemistry of carbon capture is well understood and the chemistry of CO_2 conversion is increasingly capable, but both are bounded by thermodynamics and scale. Amine scrubbing and direct air capture show how energy demand grows as the CO_2 source becomes more dilute, and conversion requires hydrogen, reactive partners or electricity. Current industrial use of about 230 Mt per year is small

against 38.1 Gt of annual emissions. Utilisation pathways differ in maturity, profitability and permanence, and life-cycle assessment decides whether a benefit exists. CCU is therefore best seen as a niche but useful contributor, particularly for polymers, building materials and specialty chemicals, that complements deep emission cuts and storage.

Declaration, Conflict of Interest, Funding and Other Statements

Use of Artificial Intelligence (AI): Artificial intelligence (AI) tools were used to assist in preparing this narrative review, including organizing the subject matter, developing the manuscript structure, refining scientific explanations, and improving the clarity and presentation of the text. AI assistance supported the discussion of carbon capture technologies, the chemistry of carbon dioxide separation and conversion, potential utilisation pathways, and the practical and technological limitations of carbon capture and utilisation (CCU). The author is responsible for critically reviewing and verifying the scientific content, checking the accuracy of the cited literature and bibliographic information, assessing the interpretation of reported findings and ensuring the scientific integrity of the final manuscript.
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Author Note

The conceptualised manuscript entitled: ***"Carbon Capture and Utilisation: A Narrative Review on Chemistry and Practical Limits"*** provides a critical overview of the chemical principles, technological approaches, potential applications and practical limitations of carbon capture and utilisation (CCU). The review aims to explain how carbon dioxide (CO_2) can be separated from industrial and other emission sources and subsequently used as a feedstock for the production of chemicals, fuels, building materials and other value-added products.

The manuscript discusses the underlying chemistry of CO_2 capture, including absorption, adsorption, membrane separation, and other relevant separation approaches. It also examines selected utilisation pathways, such as catalytic CO_2 conversion, mineralisation, electrochemical conversion, and the synthesis of fuels and chemical intermediates. Attention is given to the influence of reaction conditions, catalysts, energy requirements, conversion efficiency, product selectivity, and process integration on the practical feasibility of these technologies.

The review further considers the principal challenges associated with CCU implementation, including the thermodynamic stability of CO_2, the need for suitable energy inputs, catalyst performance and durability, infrastructure requirements, economic competitiveness, product-market limitations and the environmental implications of the overall process. It emphasizes that the utilisation of captured CO_2 does not automatically guarantee net greenhouse-gas reductions. The climate benefits depend on factors such as the source of CO_2, energy supply, process efficiency, product lifetime, displacement of conventional production and the eventual fate of the carbon. Accordingly, the assessment of CCU technologies should consider life-cycle emissions alongside chemical performance and economic feasibility.

This manuscript is intended for academic, educational and scientific purposes. It is a narrative review based on previously published literature and does not report new experimental findings. The review seeks to provide a balanced understanding of both the opportunities and the limitations of CCU, with particular emphasis on the distinction between laboratory-scale feasibility and commercially viable, environmentally beneficial implementation.

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