



Review article

Advancements in carbon capture and utilization technologies: Transforming CO₂ into valuable resources for a sustainable carbon economy



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ABSTRACT

The escalating atmospheric CO₂ concentration arising from fossil fuel combustion and industrial activities necessitates immediate mitigation strategies to address global warming and environmental degradation. Carbon Capture and Utilization (CCU) technologies have emerged as a pivotal approach to transforming CO₂ from a greenhouse gas into a valuable feedstock for fuels and chemicals. This review critically examines recent advancements in CO₂ capture techniques—including absorption, adsorption, membrane separation, and mineral carbonation—and their integration with various conversion routes such as thermocatalytic hydrogenation, electrochemical and photocatalytic reduction, and biological fixation. Particular emphasis is placed on the synthesis of methanol, ethanol, methane, syngas, cyclic carbonates, and biofuels, discussing their catalytic systems (Cu-, Ni-, and Ti-based catalysts, metal-organic frameworks, and nanostructured semiconductors), reaction mechanisms, and process efficiencies. The review also evaluates techno-economic feasibility, energy input-output ratios, and net CO₂ reduction potentials, highlighting strategies for coupling renewable hydrogen and solar-driven systems to improve sustainability. Finally, it outlines the current technology readiness levels (TRLs), life-cycle assessment (LCA) outcomes, and research priorities needed to accelerate the industrial implementation of CCU technologies toward a low and circular carbon economy.

Abbreviations: CCS, Carbon Capture and Storage; CCC, Carbon Capture and Conversion; CCUS, Carbon Capture Utilization and Storage; IC³M, Integrated Combined Carbon Capture and Materialization; CCU, Carbon Capture and Utilization; ICCU, Integrated Carbon Capture and Utilization; ICCS, Integrated Carbon Capture and Storage; ICCC, Integrated Carbon Capture and Conversion; MEA, Mono-ethanol-amine; TEAs, Techno-Economic Assessments; EEMPA, N-2-ethoxy ethyl-3-morpholinopropan-1-amine; RWGS, Reverse Water Gas Shift; DFM, Dual Function Materials; GHG, Green-House Gas; AHR, Assisted Hydrocarbon Recovery; RHE, Reversible hydrogen electrode; SNG, Synthetic Natural Gas; GC, Gas Chromatography; BASF, Baden Aniline and Soda Factory; ICI, Imperial Chemical Industry; NPs, Nanoparticles; NCs, Nanocomposites, PPy, Polypyrrole; BECCS, Bioenergy with Carbon Capture and Storage; AC, Activated Carbon; CDs, Carbon Dots; MEA, Mono Ethanol Amine; DEA, Diethanolamine; TEA, Triethanolamine; MDEA, Methyl diethanol Amine; MA, Methanolamine; MEG, Mono Ethylene Glycol; DEG, Diethylene glycol; DAC, Direct Air Capture; CoFs, Covalent organic frameworks; MOs, Metal oxides; MoFs, Metal organic frameworks; 2-EEMPA, N-2-ethoxy ethyl-3-Morpholinopropan-1-amine; DMF, Dimethyl Formamide; TEM, Tunneling Electron Microscope, SEM, Scanning Electron Microscope, STEM, Scanning Tunneling Electron Microscope, EDX, Energy Dispersive X-ray spectroscopy; MJ, Mega Joules; SOECs, Solid Oxide Electrolytic Cells, GO, Graphene Oxide; GDE, Gas Diffusion Electrode; SHE, Standard Hydrogen Electrode; ppm, Parts per million; CBB, Calvin Benson Bassham; ATP, Adenosine Triphosphate; RT-PCR, Real-Time Reverse Transcriptase-Polymerase Chain Reaction; FDH, Formate Dehydrogenases; DRFIT-MS, Diffuse Reflectance Infrared Fourier Transform Spectroscopy-Mass Spectrometry; PVP, Poly Vinyl Pyrrolidone; PEI, Polyethylene Imine; SP, Sodium Phytate; CN, Carbon Nitride; PHU, Polyhydroxy Urethane; PCK, Phosphoenolpyruvate Carboxy Kinase; MDH, Malate dehydrogenase; CA, Carbonic Anhydrase; UPLC-MS, Ultra High Performance Liquid Chromatography Mass Spectrometry; PAAS, Pseudomonas Aeruginosa Aryl Sulfatase; KDC, 2-Keto acid Decarboxylase; GPP, Geranyl Pyrophosphate; NAD, Nicotinamide Adenine Dinucleotide; GDH, Glutamate Dehydrogenase; RGP, Arg-X-Specific Cysteine Proteinase; qPCR, quantitative Polymerase Chain Reaction; HPLC, High Performance Liquid Chromatography; LNG, Liquefied Natural gas; GHG, Green House Gas; FAME, Fatty Acid Methyl Esters

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1. Introduction

CO₂ plays an important role in the onset of climate change. Different human activities, such as deforestation, burning fossil fuels in vehicles, industrial emissions, conventional cooking practices, power plants (thermal), and forest fires, contribute to the release of CO₂ into the atmosphere. To address the issue of global warming, it is crucial to implement strategies for capturing and removing CO₂ from the air. CO₂ capture technologies, in common practice, use methods like post-combustion, pre-combustion, oxyfuel combustion capture, and direct air capture [5,39,89,149,191]. These approaches collectively contribute to mitigating the impact of CO₂ emissions on the environment. These strategies aim to trap CO₂ produced by industrial activities, power generation, and burning fossil fuels, preventing its release into the atmosphere. After capturing CO₂, the pivotal next phase involves converting it into valuable products, effectively completing the carbon cycle [68].

Ethanol, acetaldehyde, and methane are notable products derived from the captured CO₂. Ethanol, positioned as a biofuel, holds promise in diminishing dependence on hydrocarbon (fossil) fuels and mitigating the release of greenhouse gases into the atmosphere. Acetaldehyde functions as a precursor, contributes to the creation of diverse chemical compounds, and finds applications in the manufacturing of plastics, pharmaceuticals, and other chemical products. Meanwhile, methane, a formidable greenhouse gas in its original state, can be transformed from CO₂ and harnessed as a cleaner energy alternative [121].

Capturing CO₂ and storing it under the seabed or ocean is one of the important methods. A significant amount of CO₂ is absorbed by the phytoplankton present in the sea and oceans. This absorption leads to a decrease in ocean pH, causing ocean acidification. Acidification can have detrimental effects on marine life, especially organisms with calcium carbonate shells, such as corals and some types of plankton. Changes in temperature, precipitation patterns, and sea levels can disrupt ecosystems and biodiversity. Some species may struggle to adapt or face extinction, while invasive species may thrive under new conditions. This leads to a shift in ecosystems and the potential loss of biodiversity.

Changes in climate and weather patterns can impact agriculture by affecting crop yields, the distribution of pests and diseases, and the availability of water resources. These disruptions can threaten global food security. Positive feedback loops can amplify the effects of increased CO₂ levels. Climate change resulting from excess CO₂ can have wide-ranging social and economic consequences. This includes displacement of communities due to sea-level rise, increased frequency of natural disasters, and infrastructure challenges. Addressing the

consequences of excess CO₂ in the atmosphere requires global efforts to reduce carbon emissions and carbon footprints, transition to sustainable energy sources, and adapt to the changing climate [65].

CO₂ capture and its conversion to valuable products play an important role in addressing the challenges of climate change, reducing carbon footprints, and promoting sustainable development. Fig. 1 shows CO₂ emissions from industries and subsequent capture and conversion into valuable products like CH₄, CH₃CH₂OH, biofuel, Syngas, cyclic carbonates, etc. By capturing CO₂ emissions from industries and thermal power plants, one can significantly reduce the carbon footprint in the air, helping to mitigate the impacts of climate change. CO₂ capture allows for the storage of carbon securely (carbon sequestration), preventing it from being released into the atmosphere. This helps in reducing the overall Carbon footprint and contributes to the long-term goal of achieving Carbon neutrality. A key challenge in powering carbon capture units with renewables is the intermittent nature of the energy supply. To overcome this, advanced thermal energy storage systems are being explored, with recent developments in nano-encapsulated Phase Change Materials (Nano-PCMs) offering a promising pathway to manage energy under fluctuating conditions and ensure stable operation [174]. CO₂ capture techniques can be integrated with renewable energy sources, such as solar and wind power, to generate a sustainable and reliable energy source. By capturing and storing excess CO₂ during periods of high renewable energy generation, it becomes possible to release it when renewable energy production is lower. Converted CO₂ can be used as a feedstock for the production of valuable products such as chemicals, biofuels, syngas, and ethanol [37]. This promotes resource utilization and contributes to the development of a circular economy, where waste products are transformed into valuable resources. Carbon Capture and Conversion (CCC) technologies can be employed to produce alternative fuels, reducing our reliance on traditional fossil fuels. This shift towards cleaner energy sources helps in achieving energy security and lowers the environmental impact associated with conventional energy extraction and use [88,126,153].

The development and implementation of carbon capture and conversion (CCC) technologies create new economic opportunities. Industries focused on Carbon Capture and Utilization (CCU) can stimulate job creation, innovation, and economic growth, contributing to the shift toward a more sustainable Carbon economy. The pursuit of efficient and cost-effective CCC technologies drives technological innovation. Continued research and development in CO₂ capture can lead to breakthroughs that improve the overall sustainability of various industries. Many regions and countries are implementing stricter regulations and targets to reduce carbon emissions. Adopting CCC

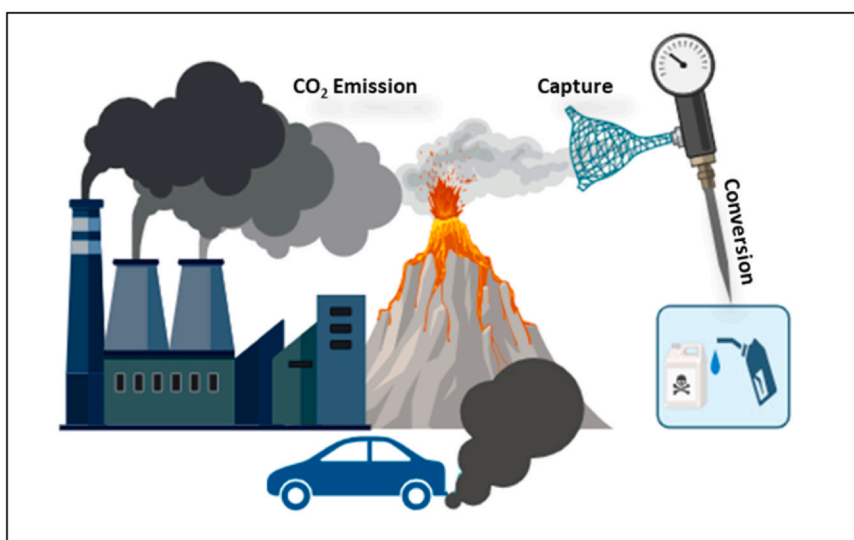


Fig. 1. CO₂ emissions from industries and subsequent capture and conversion into useful products like CH₄, CH₃CH₂OH, biofuel, Syngas, cyclic carbonates, etc.

technologies helps industries comply with these regulations, avoid penalties, and demonstrate a commitment to environmental responsibility. CCC to useful products are essential components of a comprehensive strategy to address climate change, promote sustainable development, and transition towards a more environmentally friendly and economically viable future [37,88,143].

Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS) represent 2 closely related yet distinct strategies for mitigating atmospheric CO₂ emissions. CCS primarily focuses on the long-term sequestration of captured CO₂ in geological formations such as depleted oil and gas reservoirs or deep saline aquifers. While it offers significant potential for large-scale emission reduction, its major environmental trade-off lies in the permanence of storage and the potential risks of leakage, as well as limited economic incentive since the captured carbon remains unused. In contrast, CCUS extends the concept by integrating utilization pathways, converting CO₂ into fuels, chemicals, polymers, and construction materials, thus creating value-added products and contributing to a circular carbon economy. This utilization approach not only offsets part of the capture and conversion costs but also enhances public acceptance and economic feasibility.

From a regulatory and policy standpoint, CCS projects are often governed by stringent frameworks emphasizing long-term monitoring and liability for stored CO₂, whereas CCUS systems intersect with broader energy and industrial policies promoting innovation, carbon markets, and circular economy initiatives. Recent policy instruments—such as carbon pricing mechanisms, tax incentives (e.g., U.S. 45Q credits), and emissions trading systems in the EU—are increasingly designed to encourage CCUS deployment over conventional CCS, given its potential to integrate mitigation with value creation.

Therefore, while both CCS and CCUS contribute to climate mitigation, their techno-economic and policy implications differ significantly. Recognizing these distinctions is critical to understanding the evolution of carbon management strategies and the transition toward a sustainable carbon economy.

This review provides a comprehensive study of the pivotal role played in CO₂ capture and subsequent conversion into useful products. We underscore the significance of CCC and CCU technologies, highlighting their potential to significantly contribute to mitigating the global climate challenge. Simultaneously, these technologies offer the prospect of generating valuable products for diverse industrial applications. Up till now a comprehensive review is lacking in the field of CCC and CCU techniques which focusses on CCC in useful products like methane, ethanol, biofuel, Syngas, methanol, and cyclic carbonates. This comprehensive review aims to catalyze scientific investigations within the realms of environmental preservation, sustainable energy generation, mitigation of global warming, reduction of carbon footprints, and the amelioration of environmental transformations. For the first time, we are reporting different methods of CO₂ capture from the atmosphere like amine, glycol, NaOH, and enzyme-based solvents, solid adsorbents like Activated Carbon (AC), Covalent Organic Frameworks (COFs), Cryogenic separation, Metal-Organic Frameworks (MOFs), membrane separation, and Direct Air Capture (DAC) are discussed in detail. After the capture of CO₂, its conversion to valuable products like methane, ethanol, biofuel, Syngas, methanol, and cyclic carbonates is discussed in detail.

2. Different approaches to capture CO₂

The sequestration of CO₂ from the environment constitutes a critical strategy in combating climate change and restraining the release of CO₂ emissions. Different methods and solvents are utilized for collecting CO₂ from the ambient surroundings. Different solvents used in CO₂ capture serve the main role in the absorption of CO₂ and facilitating its separation from gas mixtures [76,189]. Commonly used solvents for CO₂ capture include Piperazine, Monoethanolamine (MEA) [191], Methyl diethanolamine (MDEA) [180], Triethanolamine (TEA) [112],

Diethanolamine (DEA), Ionic Liquids (liquids in a state of matter characterized by ionic properties, exhibiting effectiveness as solvents for CO₂ capture due to their unique characteristics) [26], aqueous ammonia (ammonia dissolved in water functions as a solvent for CO₂ capture), K₂CO₃ (Potassium carbonate finds application in various capture processes, particularly in pre-combustion capture), Sodium hydroxide, or caustic soda, Methanol Amine (MA), chilled ammonia, sodium carbonate (Na₂CO₃), Glycols (Glycols, such as mono ethylene glycol (MEG) and Diethylene Glycol (DEG) [58], proves suitable for CO₂ capture, and enzyme-based solvents, enzymes including carbonic anhydrase, can be incorporated into solvents to enhance their CO₂ absorption capacity [12,35,120,131,139,177].

One method of capturing and storing CO₂ to mitigate its release into the atmosphere is through a process known as CCS. Entrapment of CO₂ in sea beds, specifically in geological formations beneath the ocean floor, is part of this larger CCS strategy. The process involves capture, transport, and injection into sea beds. The first step is to capture CO₂ emissions from different sources. These include post-combustion capture, pre-combustion, and oxyfuel combustion. Once captured, the CO₂ needs to be transported to a suitable storage site. This may involve pipelines, ships, or other transportation methods, depending on the distance between the capture site and the storage site. The captured CO₂ is then injected into geological formations beneath the seabed. These formations provide natural traps for the CO₂. The injected CO₂ is stored in these formations over long periods. Regular monitoring is essential to ensure the secure storage of CO₂ and to detect any potential leakage. Techniques such as seismic imaging, pressure monitoring, and geochemical analysis are used to assess the integrity of the storage site [13,25].

It's important to note that while geological storage of CO₂ is considered a promising option for large-scale carbon capture, it comes with challenges and uncertainties. These challenges include the leakage of CO₂ gas, the expenditure involved in capturing and storing it, and the need for suitable geological formations. Additionally, the environmental impact and long-term effectiveness of this method need to be carefully studied and monitored to ensure its safety and efficacy in reducing atmospheric CO₂ levels.

Several prevalent methodologies for CO₂ capture include (i) using amine-based solvents or solutions for CO₂ absorption. Amines, exemplified by mono-ethanolamine (MEA), are frequently employed for CO₂ capture through the establishment of chemical bonds. This process entails directing CO₂-enriched air through an amine solution, where the amines engage in reactions with CO₂, resulting in the formation of a chemically stable compound [13], (ii) Utilizing solid sorbents for the adsorption of CO₂. Solid materials, like activated Carbon (AC) or MOFs and COFs, can adsorb CO₂ from the atmosphere. The process of CO₂ adsorption requires subjecting the material to the gas stream, facilitating the capture of CO₂ on its surface [204]. Additionally, (iii) membrane separation technology employs selective membranes that facilitate the permeation of CO₂ while impeding the adsorption of other gases. This technique is commonly applied in after-combustion CO₂ capture scenarios, enabling the separation of CO₂ gas from flue gas. (iv) Cryogenic separation uses low-temperature techniques to isolate CO₂ from other gases within a mixture. This process involves cooling CO₂ to extremely low temperatures, causing its condensation and subsequent separation from the gas mixture [87]. (v) The chemical loop burning methodology utilizes metal oxides (MOs) as oxygen exporters within a closed-loop system. This system involves the cyclic circulation of metal oxide between 2 reactors, facilitating the transfer of oxygen for fuel combustion while concurrently capturing CO₂, (vi) The direct air capture (DAC) method involves technologies that directly seize CO₂ from the surrounding atmosphere through the use of chemical sorbents or filters. Following capture, the CO₂ can be further concentrated and subsequently stored, transported, converted or harnessed for diverse applications; (vii) Biological mechanisms involved in the sequestration of CO₂ encompass processes facilitated by specific microorganisms and

plants, prominently exemplified by photosynthesis. The conceptual framework of Bio-Energy with Carbon Capture and Storage (BECCS) integrates the utilization of biomass with advanced carbon capture technologies to mitigate anthropogenic CO₂ emissions [25], (viii) Marine-based strategies for CO₂ capture encompass various methodologies [26,87,204]. Augmented weathering entails the intensification of mineral weathering processes in specific minerals with inherent CO₂-absorbing properties, occurring either in terrestrial or marine environments. Ocean-centric techniques, exemplified by ocean alkalinity enhancement, strive to elevate the alkalinity of seawater, thereby fostering enhanced absorption of CO₂ [204], and (ix) Carbon capture through mineralization involves the chemical reaction of CO₂ with specific minerals, leading to the synthesis of stable carbonates [87]. This transformative procedure is commonly referred to as mineralization or mineral carbonation. In a parallel tone, the utilization of ionic liquids emerges as a promising avenue for carbon capture. Ionic liquids, characterized as salts in a liquid state, exhibit unique properties, rendering them effective solvents for capturing CO₂ [11,26].

The above-stated methodologies exhibit diversity in terms of efficiency, economic considerations, and suitability for distinct emission origins. The selection of a specific methodology frequently hinges upon the unique attributes of the emission source and the intended objective for the sequestered CO₂, whether it be storage, utilization, or disposal [2,8,15,36,77,93].

CO₂ capture is classified as pre-combustion, post-combustion, and Oxy-fuel combustion. Each technology has its advantages and disadvantages.

2.1. Post-combustion CO₂ capture

Post-combustion CO₂ capture technique involves the capture of CO₂ after the combustion of fuel. The most common source of Post-combustion CO₂ is flue gases (a mixture of gases coming out of the smokestack). The flue gas contains CO₂, nitrogen, water vapor, and other stuff. A solvent (amine-based) *absorbs* the CO₂ from flue gas. The main advantage of the post-combustion CO₂ capture technique is that it can be integrated with existing thermal power plants. The main challenge in Post-combustion CO₂ capture from flue gas is dilute (around 10–15% CO₂), so it's harder and energy-intensive to capture CO₂.

2.2. Pre-combustion CO₂ capture

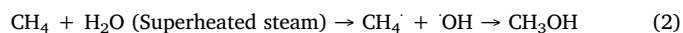
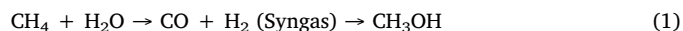
Pre-combustion CO₂ capture technique involves the capture of CO₂ before the combustion of fuel. The fuel is converted into a mixture of hydrogen and CO₂ (called Syngas) through processes that include gasification. First, fuel combines with O₂ or steam to form syngas (H₂ + CO). Then, CO reacts with H₂O to form hydrogen gas and CO₂, termed as a shift reaction. CO₂ is captured before combustion, and H₂ is burned (produces H₂O, not CO₂). The main advantage of the pre-combustion CO₂ capture technique is that it is easier to capture CO₂ at higher pressure and concentration in comparison to the post-combustion technique. The main challenge in Pre-combustion CO₂ capture is that it is expensive and more complex in operation.

2.3. Oxy-fuel combustion

In oxy-fuel combustion, the fuel is burned in a pure O₂ supply instead of an air supply. Normal air contains 78% N₂ gas. When fuel is burnt in air, one gets a lot of N₂ in the flue gas. Burning in pure oxygen means the exhaust is almost pure CO₂ and water vapor. Water is condensed, leaving nearly pure CO₂ for easy capture. The main advantage of the oxy-fuel combustion is a very pure CO₂ stream, which is easy to capture. The main challenge in oxy-fuel combustion CO₂ capture is that O₂ production is a very energy-intensive process.

3. CO₂ capture and conversion (CCC) to methane (CH₄) gas

CH₄ gas has different uses and importance across different sectors like energy production, transportation, the agriculture sector, wastewater treatment, cooking purposes, heating purposes, and laboratory applications. CH₄ is the primary component of natural gas, a vital source of energy. It is used in heating, cooking, and electricity production. CH₄ serves as a precursor gas for the synthesis of different chemicals, including hydrogen, carbon black, and methanol. These chemical products are essential in the manufacturing of different useful products.



CNG (compressed natural gas) and LNG (liquefied natural gas) produced from CH₄ gas are used as alternative fuels for vehicles. Methane-powered vehicles produce less pollution as compared to conventional gasoline or hydrocarbon fuel-based engines. CH₄ is a precursor for the production of ammonia, a key component in nitrogen-based fertilizers. These fertilizers play a crucial role in enhancing crop yields. CH₄ is produced during the anaerobic digestion of organic waste in landfills and wastewater treatment plants. Capturing and utilizing this CH₄ helps reduce greenhouse gas emissions and provides a renewable energy source. CH₄ is commonly used in households for cooking and heating. In its natural gas form, it provides a convenient and efficient energy source for these applications. CH₄ can be produced from organic waste through anaerobic digestion or fermentation. This process results in biogas, a mixture of CH₄ and CO₂. Utilizing biogas for energy helps mitigate the release of CH₄ into the atmosphere. CH₄ is used in laboratories for various analytical techniques, such as gas chromatography.

The implementation of an Integrated Combined Carbon Capture and Materialization (IC³M) process for converting CO₂ into useful chemical compounds emerges as an appealing solution for addressing the global energy landscape. This innovative approach not only mitigates the decreasing demand for energy but also diminishes dependence on fossil (hydrocarbon)-based fuels, leading to a substantial reduction in CO₂ emissions. Additionally, a water-lean post-combustion capture technique was proposed to upsurge the efficiency of the overall process.

N-(2-Ethoxyethyl)-3-Morpholino-propan-1-amine (2-EEMPA) serves as an efficient solvent, capturing over 90% of CO₂ and undergoing conversion to hydrocarbons. The predominant product is CH₄ gas, particularly in the presence of heterogeneous Ruthenium catalysts at relatively low reaction temperatures (171 °C) and low pressure (< 15 bar H₂ pressure). Comparatively, 2-EEMPA exhibits superior catalytic performance when contrasted with a 5.0 M Mono-ethanol-amine (MEA) solution in aqueous media. Operando magnetic nuclear resonance analysis reveals the *in situ* synthesis of N-formamide intermediates within 2-EEMPA, subsequently leading to CH₄ gas production through additional hydrogenation and the formation of higher hydrocarbons. Techno-economic assessments (TEAs) underscore the potential for enhancing the proposed integrated process and affirming its heat efficiency.

Carbon Capture, Utilization, and Storage (CCUS) is extensively regarded as a viable strategy for diminishing the release of CO₂ into the air. This approach serves to alleviate the adverse effects of global warming and the acidity of oceans. Nitrogen (amine) containing organic solvents are frequently utilized as extraction agents for the absorption of CO₂, subsequently undergoing release, compression, and transportation or storage, thereby mitigating CO₂ emissions originating from extensive industrial operations. Considerable investments are presently directed towards the advancement of carbon capture technologies. However, the economic feasibility of these technologies remains constrained by the substantial costs incurred in processes such as separation, compression, transportation, and storage. Conversely, CO₂

emerges as an appealing and cost-effective carbon feedstock for synthesizing value-added products and biofuels, including but not limited to CH_4 , CH_3OH , $\text{CH}_3\text{CH}_2\text{OH}$, dimethyl carbonate, HCCOH , carbon monoxide, aromatic carbonates, methyl formate, and poly-carbonates. The process of directly converting captured CO_2 addresses challenges linked with CCUS, for example, hydrogenation, which counterbalances the energy demands for the revival of CO_2 -capturing solvents. A growing interest has emerged in Integrated CO_2 Capture and Conversion (ICCC). Progress has been achieved in transforming CO_2 into valuable products and biofuels [191]. Most amine and alcohol-based solvents used in thermocatalytic conversion are impractical for CO_2 capture because of their cost, excessive viscosity (e.g., polyethyleneimine), or volatility (e.g., triethylamine/ethanol). There exists a critical need to apply this knowledge in designing reactions and conditions suitable for effective carbon capture solvents.

Materials exhibiting dual functionalities have been documented in scientific literature, demonstrating their efficacy in the simultaneous processes of CCC into CH_4 [65]. These multifunctional materials typically consist of a synergistic combination of an adsorbent and a catalytically active component. Notably, oxides and metal carbonates (like Na_2CO_3) function as effective CO_2 sorbents within these systems. Meanwhile, metals like Ni, Ru, and Rh play a pivotal role as catalytic agents, facilitating the CCC into CH_4 [68]. The adsorption of CO_2 and subsequent hydrogenation reactions are executed under elevated temperatures (300–750 °C). Alternative methodologies involve the application of conventional aqueous amine solutions for CO_2 capture and the deployment of gaseous CO_2 hydrogenation utilizing CH_4 synthesis. Nevertheless, these strategies face economic challenges attributed to the energy-intensive processes of CO_2 separation and storage. The decelerated CO_2 conversion observed in the aqueous solvent is attributed to the impediment posed by the surplus water content, which unfavorably influences the dehydration step. This underscores the superior efficacy of water-based solvents in the realm of ICCU. Notably, a protracted reaction in α -EEMPA-based solvent yielded a remarkable > 89% CO_2 conversion efficiency [65].

The methylation of CO_2 in the gaseous phase commonly transpires through a reactive intermediate, namely CO. In the context of solvent-assisted methanation, neither GC nor Nuclear Magnetic Resonance revealed detectable amounts of CO, attributable to the low reaction temperature facilitating the Reverse-Water-Gas-Shift (RWGS) reaction. Nevertheless, the hydrogenation of CO bonded to Metal, originating *in situ* from CO_2 , can proceed to form CH_4 without the concurrent generation of gaseous CO [37]. In the absence of externally introduced CO_2 , a notable conversion exceeding 80% to CH_4 in the gaseous phase was documented after the reaction. This observation underscores the feasibility of both carbon monoxide and N-formamide pathways in the solvent-mediated CO_2 methylation process. The disclosed findings represent a pioneering instance of the ICCU to CH_4 in a thermo-catalytically driven low-temperature reaction, achieved in a cost-effective after-combustion CCU process [88].

The preferential synthesis of hydrocarbons, predominantly methane, was successfully realized through the utilization of captured CO_2 under conditions of reduced temperatures and pressures. This process employed an innovative H_2O -based after-combustion capture [76]. Operando Nuclear Magnetic Resonance spectroscopy elucidated the emergence of CH_4 via a discernible formamide reactive intermediate. The conceptualized IC^3M methodology strategically aligns the energy expenditure in capture and conversion technology. Specifically, the exothermic nature of hydrogenation processes is harnessed to counterbalance the endothermic demands associated with the regeneration of solvent captured in the process [89].

The sequestration of CO_2 within a solution prevents the energy expenditures linked to the compression and transportation of CO_2 , an integral aspect of a traditional Sabatier process. The amalgamation of these operational entities has the potential to enhance thermal efficiency by 5%, diminish overall capital outlay, and curtail the selling

price of synthetic natural gas (SNG) by 31.9% and 11.9%, correspondingly, in comparison to a standard Sabatier process [164].

The inaugural instance of Integrated Carbon Capture and Utilization (ICCU) was documented in 2015 [35]. After this, a considerable multitude of innovative critical care unit technologies have been documented and disseminated within the scientific literature [120,131,177]. Dual-function Materials (DFM) have been documented in the context of ion-conductive composite uptake techniques. DFM is comprised of alkaline earth metals, specifically sodium [12,25], magnesium [13,204], or potassium [87]. MOFs are employed in the context of carbon capture due to their high affinity towards acidic CO_2 gas. This high affinity facilitates the formation of metal carbonates during the carbon capture process. Other transition metals like Ruthenium [14,26], Nickel [11,87], and Rhodium [36] were used as catalytic agents because of their high ability to assist the hydrogenation of CO_2 gas to SNG. Alkaline and transition metals in different phases were immobilized on an extensive catalytic substrate, such as γ -alumina, serving as a support matrix. A. Trevino and colleagues systematically explored diverse materials as carriers for dimethylformamide (DMF), including Cerium oxide (CeO_2) with its non-uniform surface morphology, sodium zeolite-X, silicon carbide, silica (SiO_2), and mixed metal oxides like $\text{ZrO}_2/\text{CeO}_2$, $\text{Y}_2\text{O}_3/\text{ZrO}_2$, among others [8]. These carriers were investigated for their potential to modulate the performance characteristics of DMF. It was observed that γ - Al_2O_3 shows good results in ICCU. Another research group used non-supported catalytic for effective ICCU technology [77]. Al-Mamoori and colleagues documented the synthesis of calcium-based CO_2 adsorbents, incorporating a blend of sodium or potassium metals [2]. The incorporation of sodium and potassium metals into the framework of DFM enhances the adsorption efficacy of the materials, leading to significant improvements in CO_2 capture. This augmentation manifests as heightened adsorption rates and notable stability, particularly under elevated temperatures, such as 300 °C. Another investigation by a distinct research group documented the adsorption of CO_2 using sodium carbonate doped with calcium oxide as an adsorbent [93]. Lopez et al. observed an enhancement in the adsorption kinetics of Na_2CO_3 following the incorporation of CaO, indicating favorable cycle stability. The study involved the doping of Sodium and Potassium in a Ruthenium/CaO/ Al_2O_3 -based DFM using the ionically coordinated chemical uptake technique, conducted at both ambient and elevated temperatures [15]. The concentration of dopants was systematically altered by manipulating the $\text{Na}_2\text{CO}_3/\text{CaO}$ composition. This experimental approach revealed a peak adsorption capacity of 16% for CO_2 , subsequently undergoing hydrogenation to synthesize SNG. Fig. 2 shows an X-ray diffraction study, TEM image of Ru/ Al_2O_3 /12% Na_2CO_3 /4%CaO, CO_2 , H_2O , methane gas and carbon monoxide concentration observed during first cycle of CO_2 adsorption and subsequent hydrogenation to SNG for DFM Ru/Na/Ca/ Al_2O_3 composite at 400.0 °C and scanning tunneling electron microscope (STEM) and energy dispersive X-ray spectroscopy (EDX) mapping of Aluminum (b), Sodium (c), Calcium (d) and Ruthenium metals (e) for reduced DFM Ru-8%Na/8%Ca samples.

Table 1 shows the different concentrations of SNG produced per gram of material, the quantity of SNG produced per minute, the hydrogen gas used for reduction (%), and the temperature (°C) of reduction. A maximum of 614 $\mu\text{mol/g}$ of SNG was produced by the Ru/ $\text{Na}_2\text{CO}_3/\text{Al}_2\text{O}_3$ material used in ICCU [120]. A minimum of 176 $\mu\text{mol/g}$ of SNG was produced by the Ru/K/ Al_2O_3 material used for the ICCU technique [74]. However, the quantity of CH_4 gas produced was maximum, i.e., 1200 mL/min in DFM based on Ru/Na/Ca/ Al_2O_3 material [15].

4. CO_2 capture and its conversion (CCC) to ethanol

The CCC technique is a very important technique that helps in minimizing overall carbon footprints, environmental pollution, Global warming, and dependency on fossil fuels. Production of ethanol (bio-fuel) from the CCC technique offers many advantages, contributing to

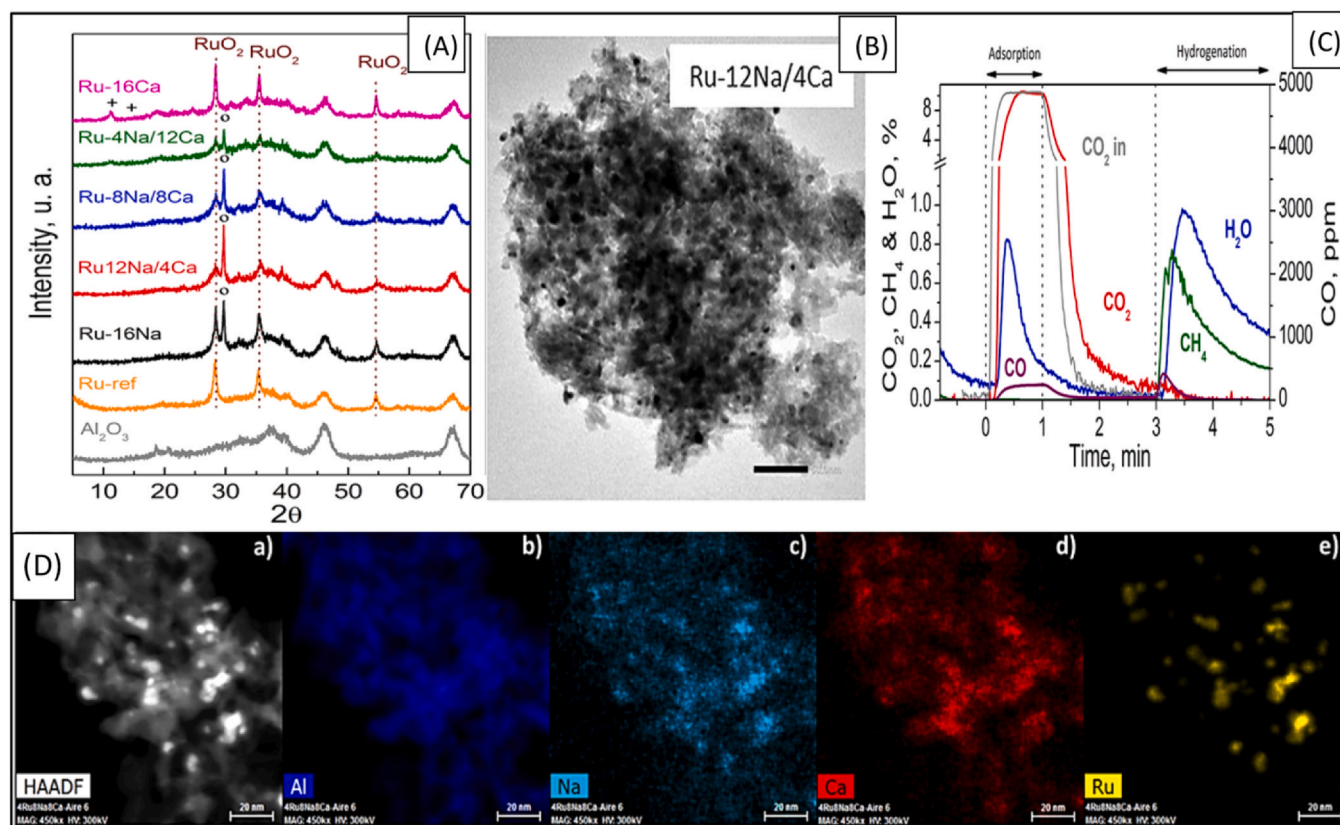


Fig. 2. XRD study of Al₂O₃/Ru and DFMs (A) TEM image of Ru/Al₂O₃/12%Na₂CO₃/4%CaO sample (B) CO₂, H₂O, methane gas and carbon monoxide concentration observed during the first cycle of CO₂ adsorption and subsequent hydrogenation to SNG for DFM Ru/Na/CaO composite at 400.0 °C (C), and STEM and EDX mapping of Aluminum (b), Sodium (c), Calcium (d) and Ruthenium metals (e) for reduced DFM Ru-8%Na/8%Ca samples (D). [Reproduced with permission Bermejo-López et al. [15]]. DFM = dual function materials; EDX = energy dispersive X-ray spectroscopy; SNG = synthetic natural gas; STEM = scanning tunneling electron microscope.

environmental sustainability and addressing climate change. Utilizing CO₂ from industrial processes or DAC, turning CO₂ gas into a valuable product for biofuel production will help to reduce overall Carbon emissions by recycling CO₂ into the atmosphere. Ethanol is a renewable and bio-based fuel derived from organic materials such as plant biomass, which can be grown and harvested sustainably. It reduces the dependence on fossil fuels, contributing to cleaner and more sustainable energy production.

The CCC to ethanol technique diversifies the sources of energy by providing an alternative to traditional fossil fuels, enhancing energy security, and reducing reliance on finite and limited resources. The overall Carbon footprint of ethanol produced from captured CO₂ can be lower than conventional fossil fuels, as it involves the removal of CO₂ from the air.

CCC can be integrated into existing ethanol production technology, making it a feasible option for transitioning from conventional ethanol production methods to more sustainable practices. It promotes the cultivation of energy crops or the use of agricultural residues for biomass feedstock, contributing to sustainable agriculture and rural development. The combination of ethanol production and Carbon capture can be part of a broader strategy known as Bioenergy and Carbon Capture Strategies (BECCS), which has the potential to eliminate CO₂ on a large scale. Advances in CCC technology can lead to increased energy efficiency in the conversion process, making the production of ethanol from captured CO₂ more economically viable and environmentally friendly. CCC technology supports the growth of a new industry centered on sustainable energy production, creating jobs, and stimulating economic development [62,74].

The addition of ethanol to petrol (fossil fuel), creating a blended biofuel known as ethanol-blended petrol (EBP), serves many purposes, primarily related to environmental and energy-related objectives. The

most common blend is E10, which contains 10% ethanol and 90% petrol. A few reasons and mechanisms behind blending ethanol with petrol include switching from non-renewable to a renewable energy source, reduction in CO₂ gas emission, increase in oxygenation and combustion atmosphere, improvement in Octane rating, increase in the performance and cleanliness of internal combustion engine, reduced dependency on oil import from foreign countries, etc.

Ethanol is derived from plant biomass, making it a renewable and bio-based fuel. Blending ethanol with petrol helps to minimize dependence on non-renewable hydrocarbon-based fuels and supports the use of sustainable energy sources. Ethanol combustion produces fewer greenhouse gas emissions compared to pure petrol. As ethanol is derived from plants, it participates in the natural Carbon cycle, and the CO₂ released during combustion was recently captured from the atmosphere during the plant's growth. Ethanol contains oxygen, and blending it with petrol increases the oxygen content in the fuel. This improves the combustion efficiency, leading to more complete burning of hydrocarbons and reduced emissions of CO and particulate matter.

Ethanol has a greater octane rating than petrol, which enhances the fuel's resistance to knocking. Blending ethanol with petrol allows for the production of fuels with higher octane ratings, enabling the use of higher compression ratios in engines and improving engine efficiency. Ethanol has a positive impact on engine performance by providing a cleaner burn and reducing engine deposits. It can also help to cool the combustion chamber, reducing the risk of engine knocking. The use of domestically produced ethanol (biofuel) reduces a country's dependence on imported oil from gulf countries, contributing to energy security and mitigating the impact of volatile global oil prices.

Many countries implement policies and standards promoting the use of biofuels like ethanol to meet renewable energy targets and reduce the

Table 1

SNG produced per gram of material, quantity of SNG produced per minute, and hydrogen gas used for reduction (%), and temperatures (°C) of reduction

Materials used for ICCU	SNG produced per gram of material ($\mu\text{mol/g}$)	T (°C)	Quantity (mL/min)	Hydrogen gas used for reduction (%)	Reference
DFM based on Ru(4%)/Na(4%)/Ca(12%)/Al ₂ O ₃	372	400	1200	10	Bermejo-López et al. [15]
Ru(5%)/CaO(10%)/Al ₂ O ₃	500	320	26	4	Cimino et al. [26]
Ru(5%)/Na ₂ CO ₃ (10%)/Al ₂ O ₃	614	320	200	15	Bermejo-López et al. [11]
Ru(1%)/K(5%)/Al ₂ O ₃	176	350	100	4	Jeong-Potter and Farrauto [74]
Ru(1%)/Li(5%)/Al ₂ O ₃	340	293	33	10	Zhou et al. [204]

DFM = dual function materials; ICCU = integrated carbon capture and utilization; SNG = synthetic natural gas.

environmental impact of the transportation sector. Ethanol production often involves the use of crops, contributing to rural development and providing farmers with an additional market for their produce. While E10 (10% ethanol) is the most common blend, high concentrations of ethanol blending, like 15% ethanol or E85 (85% ethanol), are also used in some regions. However, higher ethanol blends may require specific engine alterations or the use of flex-fuel vehicles designed to handle these concentrations. The selection of ethanol blending depends on factors, i.e., infrastructure, vehicle compatibility, and regulatory considerations.

To mitigate the average temperature rise over the long term, imperative measures must be taken to curtail global CO₂ emissions by the year 2050, given that CO₂ constitutes the primary greenhouse gas (GHG). The imperative dictates a reduction in CO₂ emissions ranging from 50% to 85% relative to the baseline recorded in 2010. Consequently, it is paramount to advance the development of diverse technological solutions in the forthcoming years to effectively restrict and diminish CO₂ emissions [63]. One proposed strategy involves the sequestration and reutilization of emitted CO₂. A predominant challenge of the current era lies in the exploration of novel applications, enhancement, and advancement of existing methodologies, all while ensuring net environmental neutrality. By harnessing non-fossil energy sources, CO₂ can serve as a raw material in industrial processes, undergoing chemical or biological transformations to yield biofuels, chemicals, or pharmaceutical compounds [9].

Different potential routes for CO₂ recycling may be categorized into 3 different groups. The initial group involves the direct utilization of CO₂ in the absence of any transformative processes. In this context, CO₂ is employed for its inherent physicochemical and thermodynamic attributes, serving as a solvent, among other applications [115]. The preponderance of these routes is extensively documented and presently implemented at an industrial scale. An illustrative example is Assisted Hydrocarbon Recovery (AHR), a method widely employed in conjunction with CO₂ derived from natural reservoirs. The subsequent category

encompasses the bioconversion of CO₂, wherein biological organisms, notably algae, utilize photosynthesis to produce desired compounds such as carbohydrates, fats, and cellulose [127].

The electrochemical recycling of CO₂ involves leveraging carbon-free energy sources, such as renewable or nuclear energy, to provide heat and electricity for the breakdown of CO₂ and water. This dissociation can be achieved through thermal breakdown, light-assisted, or electric field-assisted breakdown of water and CO₂. The electrolysis for the dissociation of CO₂ and water vapor was proposed. There are 2 methodologies for generating synthesis gas (Syngas) via electrolysis: one involves dissociating CO₂ and water independently in distinct electrolytic cells, while the other entails simultaneous dissociation in a single electrolytic cell. Recent scientific inquiries indicate that the simultaneous electrolysis of water and CO₂ is more advantageous regarding energy utilization and conversion efficiency compared to the separate electrolysis of water vapor and CO₂ [144].

Over the past decade, global ethanol production has witnessed a 2-fold increase, with projections anticipating a 3-fold surge by the year 2025. The predominant origin of ethanol production emanates from biomass rich in starch. An alternative source involves the reduction of CO₂ to C₂H₅OH, employing a Cu-based electrode [79]. Fig. 3 depicts CO₂ capture, electrocatalytic reduction of CO₂ using Copper-based electrodes into ethanol, and blending with petrol to be used as biofuel. Ethanol exhibits compatibility with hydrocarbon-based fuels such as petrol. The escalating demand for blended fuels stems from the elevated cost and constrained availability of hydrocarbon-based alternatives. An alternative avenue for ethanol production involves the utilization of Syngas. Syngas can be transformed into ethanol through 3 distinct pathways. The primary pathway involves the straight synthesis of C₂H₅OH from Syngas. The 2nd pathway entails the conversion of Syngas to CH₃OH, followed by the transformation of CH₃OH into C₂H₅OH through a CH₃OH homologation process. The final pathway, denoted as the ENSOL method, involves the initial conversion of Syngas to CH₃OH utilizing a commercial synthesis catalyst, followed by CH₃OH

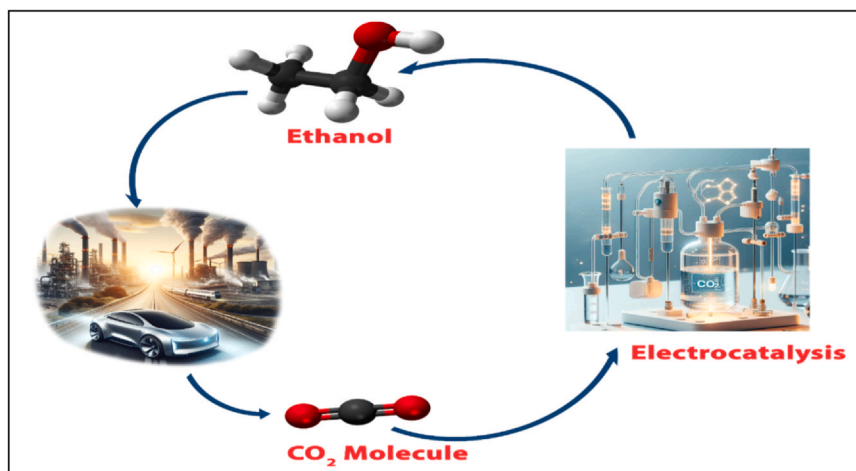
**Fig. 3.** CO₂ capture, electrocatalytic reduction to ethanol, and blending with petrol to be used as biofuel.

Table 2

Electrochemical reduction of CO₂ using a catalytic electrode, the type of electrolyte used, the potential and current supplied, the duration of reduction, and the type of electrochemical cell used

Catalytic electrode used	Type of electrolyte	Potential applied w.r.t. RHE (volt)	Current density (mA/cm ²)	Faradaic efficiency for ethanol production (%)	Cell used	Time of electrochemical reduction	Ref.
Oxide-derived Copper/Carbon	0.10 M KHCO ₃	−0.5	−1.0	34.8	H- cell	180	Zhao et al. [201]
Copper sandwiched type	0.10 M KHCO ₃	−0.3	−1.25	31.0	H- cell	120	Daiyan et al. [28]
Copper/Cu ₂ O	0.10 M KCl	−0.4	−7.3	39.2	H- cell	300	Zhu et al. [207]
Ag/Cu ₂ O	0.2 M KCl	−1.2	−3.0	34.0	H- cell	180	Lee et al. [94]
Ag(0.4)/Cu(0.86)	1.0 M KHCO ₃	−0.84	−300	37.0	Flow cell	20	Li et al. [99]
Cu ₄ /Zn	0.1 M KHCO ₃	−1.05	−28.1	30.0	H- cell	60	Ren et al. [145]
ZnO/CuO	0.1 M KHCO ₃	−1.15	−31.8	32.0	H- cell	60	Ren et al. [146]
Cu ₃ /Au	0.1 M KHCO ₃	−0.7	−1.0	45.0	H- cell	180	Zhu et al. [208]
Cu NP/N-doped CNS	0.1 M KHCO ₃	−1.2	−4.8	63.0	H- cell	60	Song et al. [163]
Cu NP/N-doped GO	0.1 M KHCO ₃	−0.25	−4.5	56.3	H- cell	NR	Yuan et al. [193]
Cu NC	0.1 M KHCO ₃	−1.2	−16.2	43.0	H- cell	60	Karapinar et al. [80]
Cu/C (0.4)	0.10 M KHCO ₃	−0.7	−1.23	91.0	RPE	65	Xu et al. [182]
Cu-GNC-VL	0.50 M KHCO ₃	−0.87	−10.4	70.5	H-based cell	60	Zhang et al. [199]
Surface-modified Cu electrode	0.1 M KHCO ₃	−1.1	−1.04	30.6	H-based cell	65	Han et al. [60]
Fe Tetraphenyl Porphyrane (TPP)/Copper	0.1 M KHCO ₃	−0.82	−124.0	41.2	Flow cell	NR	Li et al. [96]

NR = not reported.

carbonylation to CH₃COOH, and ultimately, the hydrogenation of CH₃COOH to produce C₂H₅OH [168]. Various pathways exhibit distinctions in terms of catalysts, operational parameters, and selectivity toward ethanol and C₂ oxygenates. The other route involves the straightforward synthesis of C₂H₅OH from Syngas.

Rhodium-based catalysts, characterized as noble metals, demonstrate superior selectivity for C₂H₅OH (and C₂⁺ oxygenates in general), along with commendable CO conversion. Rhodium occupies a distinctive position within the periodic table, positioned between metals such as iron and cobalt, which efficiently undergo CO dissociation leading to the formation of higher hydrocarbons, and elements like palladium, platinum, and iridium, which do not undergo CO dissociation and typically yield methanol. Catalysts featuring a moderate concentration of Rhodium demonstrate the ability to generate CH₄, C₂H₅OH, or various oxygenated chemical species. Additionally, they facilitate the hydrogenation of CO, a process influenced by the ambient environment, promoter, and reaction conditions [41].

The Fischer-Tropsch catalysts, predominantly comprised of Co, Ru, and Fe, undergo modification to enhance their performance. Properly modified catalysts have demonstrated the capability to yield higher alcohols. Notably, the synergy between Ir/Ru-SiO₂ or Ir/Co-SiO₂ catalysts has been observed in synthesizing higher alcohols. This phenomenon is attributed to the unique interaction between metals with distinct CO dissociation properties, such as Ru and Co (capable of easy CO dissociation) and Ir (not capable of dissociating CO). The amalgamation of these metals results in a catalyst that facilitates both the extraction and insertion of CO. The altered Fischer-Tropsch catalyst exhibits reasonable selectivity to C₂H₅OH, appreciable selectivity to CH₃OH, and a thermodynamically favorable high CH₄ yield [157].

The energy utilization procedure was assessed for a C₂H₅OH manufacturing rate of 501 metric tonnes/day, corresponding to an output of 165,001 tonnes/year [43]. The comprehensive thermal energy expenditure for the production of one kilogram of ethanol is determined to be 4.383 mega-joules (MJ), with an additional electrical energy intake of 36.8 MJ. Considering a conversion efficiency of 33% from fuel energy to electrical energy (comparable to that of a nuclear plant), the overall fuel energy consumption is determined to be 109.8 MJ per kilogram of ethanol. It is noteworthy that the electrolysis operation constitutes the principal energy consumer in this context [43].

Enhancing the energy efficiency of the electrolysis cell, contingent upon current density and cell voltage holds substantial potential for mitigating overall energy consumption. As a pivotal energy consumer in this context, the distillation unit presents an opportunity for

optimization to curtail energy usage. Innovative distillation techniques, such as extractive distillation, exhibit notable potential for substantial energy savings. A comprehensive evaluation of energy consumption in comparison to conventional ethanol production processes necessitates the integration of all costs, spanning from raw material transport to ethanol production [84].

In the pursuit of investigating a potential avenue for CO₂ recycling and the generation of chemical compounds such as ethanol, Solid-oxide electrolytic cells (SOECs) were reported [194]. The scrutinized process encompasses 2 primary stages. The initial phase involves high-temperature coelectrolysis of CO₂ and H₂O using SOECs to yield syngas (comprising hydrogen and carbon monoxide). The subsequent step entails the catalytic production of C₂H₅OH from the obtained Syngas [195].

The examined catalyst is a Rhodium-based catalyst enhanced with Vanadium, exhibiting superior selectivity towards ethanol and oxygenates. Economic analysis findings indicate that a C₂H₅OH production facility powered by an ambient temperature nuclear plant can achieve a C₂H₅OH cost of 1.1 dollars/kg. Further, cost reduction is conceivable by incorporating the simultaneous generation of CH₄ and H₂. Taking into account rising oil prices and subsidies provided by the Indian Government, it is anticipated that this approach could competitively rival other conventional ethanol production methods over the next 10–15 years [114]. Table 2 shows the electrochemical reduction of CO₂ using a catalytic electrode, the type of electrolyte used, the potential and current supplied, the duration of reduction, and the type of electrochemical cell used [28,60,80,94,96,99,145,146,163,182,193,199,201,207,208]. Faradaic efficiency for ethanol production depends upon several factors like the type of electrolyte used, the catalytic electrode used in the electro-reduction process of CO₂, applied current and potential, and the electrocatalytic cell used. A maximum of 91% Faradaic efficiency was achieved in Cu/Carbon (0.4%) electrode in 0.1 molar potassium bicarbonate electrolyte at −0.7 V and −1.23 mA/cm² current [28]. Cu/GNC-VL electrode in 0.5 molar potassium bicarbonate electrolyte at −0.87 V and −10.4 mA/cm² current shows 70.5% of Faradaic conversion efficiency [199]. Single metal-based, i.e., surface-modified Copper electrode in 0.1 molar potassium bicarbonate electrolyte at −1.1 V and −1.04 mA/cm² [28] current shows a minimum of 30.6% of Faradaic conversion efficiency [60].

Table 3 shows the electro-catalytic reduction of CO₂ gas to ethanol in an alkaline medium with Faradaic efficiency greater than 30%. The analysis of Tables 2 and 3 leads to the discernment that Cu-based catalysts employed in the electro-reduction of CO₂ to ethanol can be categorized into 3 distinct classes: (i) oxide-derived Copper, (ii) Copper-M bimetallics, and (iii) Copper-doped C materials. The progression of

Table 3Electrocatalytic reduction of CO₂ to ethanol in an alkaline condition with Faradaic efficiency greater than 30%

Catalytic electrode used	Type of electrolyte	Potential applied w.r.t. RHE (volt)	Current density (mA/cm ²)	Faradaic efficiency for ethanol production (%)	Cell used	Time of electrochemical reduction	Ref.
Ag (0.14)/Cu (0.86)	1.0 M KOH	−0.67	−250	41.4	Flow cell	2	Li et al. [99]
ZnO/CuO NC/Cu	1.0 M KOH	−0.69	−200	41.0	Flow cell	10	Ren et al. [146]
NC/Copper	1.0 M KOH	−0.68	−300	52.3	Flow cell	16	Wang et al. [178]
NGQ/Cu	1.0 M KOH	−0.9	−282.1	45	Flow cell	100	Chen et al. [20]
Ce(OH)x/Copper	1.0 M KOH	−1.3	−45	31.7	Flow cell	NR	Chen et al. [22]

NR = not reported; RHE = reversible hydrogen electrode.

ethanol selectivity across these Copper-based electrodes follows the order: Oxide-derived Cu (with a maximum Faradaic efficiency of 30–40%) $\approx$ bimetallic (30.0–45.0%) < Copper-doped C (40–89%). In the context of the highly selective Copper-doped C systems, the highest Faradaic efficiency was observed in the H-based cell at exceptionally small current density ($j_{\text{EtOH}} = -1.0$ to -7.0 mA/cm²). Conversely, at significantly higher current density in a flow cell ($j_{\text{EtOH}} = -120.0$ to -150.0 mA/cm²), the Faradaic efficiency maxima remained below 52%. Generally, the most substantial Faradaic efficiency maxima were attained at markedly negative potentials (from -0.7 to -1.3 V vs SHE), with the sole exception being Cu-NP-N-doped-GO, which exhibited a minimum potential of -0.25 V. The catalytic performance of oxide-derived Copper systems in C₂H₅OH formation is notable for its operation at notably reduced applied potentials (-0.3 to -0.5 V). However, this occurs at a considerably low current density. In contrast, bimetallic systems operate at greater potentials (-0.70 to -1.20 V) with a greater current density ($j_{\text{EtOH}} = -10.0$ to -110.0 mA/cm²) than MO-derived Copper. Utilizing Gas Diffusion Electrodes (GDE) in potassium hydroxide under flow conditions results in significantly elevated current densities ($j_{\text{EtOH}} = -80$ to -160 mA/cm²). Nevertheless, these conditions do not yield a substantial enhancement in ethanol selectivity, as the Faradaic efficiency attains a maximum of approximately 40–50%.

5. CO₂ capture and its conversion to biofuel

Biofuels are a category of renewable fuels derived from organic materials like CO₂ by the CCU technique and are considered an alternative to traditional fossil (hydrocarbon) based fuels. Biofuel plays a crucial role in efforts to minimize the release of CO₂ and promote sustainability in the energy sector. The 2 main biofuels are bioethanol and biodiesel.

Bioethanol is an alcohol-based biofuel primarily composed of ethanol, which is produced through the fermentation of sugars derived from plant materials such as corn, sugarcane, or cellulosic biomass. The primary sources for bioethanol production include sugarcane, corn, wheat, and other sugar or starch-rich crops.

Biodiesel is a diesel-equivalent biofuel composed of Fatty Acid Methyl Esters (FAME) or other renewable hydrocarbons. It is typically synthesized through transesterification, where triglycerides from plant oils or animal fats are converted into biodiesel and glycerol. Biodiesel can be derived from feedstocks, like vegetable oils (Soybean, canola, palm, etc.), animal fats, and used cooking oils. Algae is also being explored as a potential source for biodiesel production due to its high oil content.

Biofuels are derived from living organisms, making them renewable and part of the natural carbon cycle. Compared to fossil fuels, biofuels generally emit lower levels of greenhouse gases, contributing to efforts to mitigate climate change. Biofuels can enhance energy security by providing an alternative to fossil fuels, reducing dependence on imported oil. Biofuels can be blended with existing hydrocarbon-based fuel, requiring minimal alterations in internal combustion engines. The production of biofuels often involves agricultural activities,

contributing to rural development and providing additional markets for farmers. Despite a few challenges, biofuels remain a vital component of a sustainable and low-carbon energy future. Ongoing innovations in feedstock diversity, conversion technologies, and sustainability practices contribute to the advancement of biofuel as a cleaner alternative to conventional fossil fuels.

The concept of generating biofuels from CCU techniques represents an innovative approach toward sustainable energy production. This process involves arresting CO₂ discharges from industries or directly from the air and utilizing them as feedstock for the production of biofuels. This approach offers several potential benefits. The biofuel generated from CCU essentially recycles carbon that would otherwise contribute to greenhouse gas emissions. By incorporating captured CO₂ into biofuel production, this technique helps mitigate the environmental impact of carbon emissions. Biofuels derived from this method are inherently renewable as they are produced from biological sources such as algae, bacteria, or other biomass. This contrasts with hydrocarbon-based fuels, which are finite and lead to environmental deterioration. The overall carbon footprint of biofuels generated through CCU can be lower than that of conventional fossil fuels because the Carbon used in biofuel comes from atmospheric or industrial CO₂ rather than ancient Carbon stored in fossil deposits. The development and deployment of CCU techniques for biofuel production drive technological innovation. This includes advancements in Carbon capture technologies, biological processes, and engineering solutions, contributing to a more sustainable and efficient energy landscape. Depending on the specific biofuel production process, these technologies may be integrated into existing infrastructure for biofuel production or industrial facilities, facilitating a smoother transition to more sustainable practices. This approach aligns with the broader concept of BECCS. Combining biofuel production with Carbon capture provides a dual benefit of renewable energy generation and CO₂ removal from the atmosphere. Biofuels generated from CCU contribute to the diversification of energy sources. As a versatile energy carrier, biofuels can be used in existing combustion engines and infrastructure, reducing reliance on conventional fossil fuels.

While the concept of biofuels from CCU holds promise, it is essential to address challenges such as energy efficiency, scalability, and economic viability. Continuous research is crucial to optimize this process and make it economically viable with other forms of renewable energy. The successful implementation of such techniques could play a pivotal role in advancing sustainable and low-carbon energy solutions for the future.

CO₂ is inherently present in the Earth's atmosphere as a trace gas, originating from both natural processes and anthropogenic activities [128]. The prevailing amount of CO₂ in the air stands at 413.93 parts per million (ppm), marking a notable elevation from the pre-industrial era levels of 280 ppm. The substantial release of CO₂ into the atmosphere stems from combustion processes related to fossil fuels and various biochemical reactions. Since the onset of the industrial revolution, characterized by the ascendancy of fossil fuels as the primary energy source, CO₂ emissions have surged by 43%. Projections suggest a prospective escalation of CO₂ emission to 60% by the year 2100,

assuming the present growth rate is maintained. Notably, beyond the combustion of fossil fuels, CO₂ has also evolved as a by-product of different chemical and biological processes. In the context of biological ethanol production, approximately 1/3rd of corn starch is forfeited in terms of CO₂. Consequently, the associated environmental concerns and health risks are significant concerns to CO₂ emission [82]. Global warming represents a plausible catalyst for instigating climatic alterations, capable of exerting a profound impact on the entirety of biomass. This is manifested through the accelerated melting of glaciers, leading to consequential outcomes such as floods, land erosion, elevated sea levels, and the potential collapse of ecosystems.

Despite its adverse ecological consequences, CO₂ concurrently presents itself as a readily accessible carbon source with potential applicability as a primary substance for the production of biofuels and related products. This presents a mutually beneficial proposition, facilitating both the decrease of CO₂ discharges and the efficient utilization of abundant carbon resources. Nonetheless, CO₂, owing to its significantly oxidized state, exhibits relative inertness, rendering its industrial transformation into valuable compounds a markedly energy-intensive undertaking without an appropriate catalyst. Presently, 4 prominent methodologies, encompassing 3 chemical processes that are pure, photo, electrical, and one biological approach, are recognized for CO₂ capture [7].

Autotrophic organisms possess the capacity to assimilate CO₂ from the environment into organic products within their central metabolic processes, accomplished through CO₂ fixation pathways. Presently, 6 such pathways have been identified within the autotrophic domain, among which is the Calvin Benson Bassham (CBB) process. While photosynthesis in plants stands as a prominent natural CO₂ fixation mechanism, it exhibits inefficiency in harnessing solar energy to its full potential, manifests slow productivity, and entails substantial water consumption [130]. The utilization of naturally occurring enzymatic diversity has encountered constraints in the direct CCU into biofuels and other products through biological CO₂ fixation. This limitation stems from various factors. For instance, the biological fixation of CO₂ primarily yields biomass rather than a specifically targeted end product.

The genetic manipulation of usual CO₂ fixation, encompassing both photo-autotrophs and chemo-autotrophs processes, has been directed towards a specific objective. Through the incorporation of genes sourced from one or multiple species, metabolic CO₂ fixation entails the construction of a novel or enhanced fixation process. The integration of multi-omics approaches has facilitated the *in vitro* synthesis, *in silico* design, and *in vivo* implementation of CO₂ capture [29].

Recent advancements in metabolic engineering have delineated various tiers, encompassing diverse manifestations of synthetic metabolism. These tiers are categorized into 5 levels. Operations at level one involve optimizing extant pathways within the native host, employing strategies such as gene knockout and overexpression to enhance flux. Level 2 metabolic engineering endeavors are characterized by copying, pasting, and fine-tuning processes resulting in the modification of the normal pathway in the recipient host, yielding reactions with superior performance. The subsequent 3 levels pertain to the construction of non-natural and innovative pathways. Level 3 involves the amalgamation of known reactions, aptly termed mix-and-match enzymes. Level 4 entails the development of pathways derived from novel reactions based on known enzyme mechanisms. Lastly, level 5 encompasses the creation of pathways utilizing novel reactions catalyzed by novel enzymes, constituting a domain of novel enzyme chemistry [147].

The constraints inherent in natural CO₂ fixation pathways have prompted researchers to explore strategic engineering and advance man-made CO₂ fixation pathways. Comprehensive endeavors have been dedicated to each of the 3 pivotal stages, encompassing *in silico* estimation, *in vitro* experimentation, and *in vivo* implementation of non-natural CO₂ capture pathways. The formulation of a man-made CO₂ fixation is guided by the careful consideration of multiple criteria. Typically, carboxylases characterized by oxygen tolerance and rapid

kinetic properties are favored for integration into the designed pathway [125]. Efforts have been directed toward minimizing undesirable side reactions and optimizing ATP expenditure in the engineered pathway. Following topological, energetic, and kinetic assessments, it is anticipated that the resultant pathway will exhibit accelerated overall kinetics, heightened flux, and superior performance in contrast to native CO₂ fixation pathways [40].

Carbon fixation stands as a pivotal biochemical process with the potential to provide essential carbon precursors for the synthesis of biofuels and other valuable bio-derived chemicals. Given its status as a ubiquitous metabolic intermediate across various cellular pathways, pyruvate emerges as a particularly intriguing compound. Through CO₂ fixation, pyruvate can be generated and subsequently integrated into diverse metabolic pathways, ultimately giving rise to dedicated bio-products. Acetyl-CoA, another noteworthy metabolic intermediate, can similarly be produced through CO₂ fixation and subsequently channeled towards the creation of desired bio-products. Consequently, a significant portion of metabolic engineering endeavors is directed toward achieving 2 primary objectives. Firstly, there is a focus on increasing the efficiency of CO₂ capture to generate common metabolic intermediates, such as pyruvate and acetyl-CoA. Subsequently, efforts are directed towards converting these common intermediates into specific bio-products by linking them to defined metabolic pathways. A concrete example of said approach is evident in the production of bioethanol from pyruvate. This breakthrough became feasible through the cloning of a gene responsible for the main enzymes involved in CH₃CH₂OH biosynthesis from pyruvate, originally sourced from *Zymomonas* species. The successful expression of these genes in *Escherichia coli* demonstrated the synthesis of bioethanol, showcasing the practical application of manipulating metabolic pathways for bio-product development [172].

Motivated by the principles of microbial electrosynthesis, wherein an electrocatalyst facilitates the conversion of electrical to chemical energy, an analogous hybrid system was explored for CO₂ capture to produce bio-fuels and other bio-chemicals. This hybrid system encompasses 2 distinctive approaches. In the first variant, CO₂ undergoes electrochemical reduction to yield formate, subsequently undergoing biological transformation into a specific bio-product, such as isobutanol, 3-methyl-1-butanol, and pyruvate, through the utilization of microbes. The 2nd type of hybrid strategy involves the electrochemical splitting of water into H₂ and O₂. The generated H₂ then participates in the litho-autotrophic CO₂ fixation [45]. Employing this methodology, the synthesis of bio-fuels and assorted chemicals from CO₂ was successfully realized within the genetically modified microorganism *Raistonia eutropha*. The electrochemical reduction of CO₂, leading to the formation of synthesis gas (Syngas), coupled with subsequent fermentation processes, yielded the production of butyl alcohol and hexane-1-ol in a synergistic hybrid system.

CO₂ represents an easily accessible reservoir of carbon, serving as a viable predecessor for the biologically synthesizing biofuels and other bio-products. Leveraging CO₂ through the metabolic engineering of microbial cell factories holds promise as a mutually beneficial strategy, concurrently mitigating CO₂ emissions and optimizing the utilization of this abundant carbon resource. The successful instances of metabolic engineering in converting CO₂ to ethanol aimed at channeling CO₂ into the production of biofuels and other valuable biochemicals. Various engineering endeavors are showcased, encompassing fundamental strategies such as copy-and-paste methods, fine-tuning approaches, and the development and assessment of innovative synthetic pathways dedicated to CO₂ fixation [125]. While different chemical products have been efficiently synthesized through CO₂ fixation in laboratory settings, the scaling-up of biological cell factories into large-scale CO₂ fixation plants for profitable applications remains unrealized. The existing synthetic pathways exhibit imperfections that hinder *in vivo* implementation and are characterized by various limitations. For instance, certain enzymes within these pathways display elevated optimum

temperatures, surpassing the viable range for most organisms with relatively lower body temperatures (30–40 °C). The necessity to maintain such elevated temperatures also entails a substantial energy expenditure [110]. Living cells exhibit a conserved optimal temperature range for the efficient functioning of all enzymes within the organism. Consequently, the successful implementation of 2 distinct enzymes with disparate optimal temperature ranges *in vivo* is unfeasible. In certain synthetic pathways, particular enzymes pose a threat to cell viability, whereas others face competition from host counterparts for substrates. Consequently, there exists untapped potential for advancing metabolic engineering endeavors to augment microbial cell factories, thereby improving CO₂ fixation into bio-fuels [125]. This endeavor is poised to induce CO₂ fixation on an industrial scale. Table 4 depicts different bio-products, namely biomass, butanol, ethanol, malate, formate, alkanes, lipids, sugar, etc., obtained after CO₂ capture techniques involved, species utilized, enzymes or genes involved, and their enzymatic pathway. Fig. 4 illustrates the synthesis of biofuels and biochemicals derived from CO₂. The entire metabolic pathway centers around 2 key stages. Firstly, the product obtained through CO₂ capture undergoes conversion into a ubiquitous intermediate, such as Pyruvate/acetyl-CoA. Subsequently, a synthetic pathway is meticulously engineered and connected to these prevalent metabolic intermediates. Cheng et al. reported *Clostridium carboxidivorans* species-based ethanol production from CO₂ using the real-time reverse transcriptase-polymerase chain reaction (RT-PCR) technique and Aor and adhE2 enzymes in a Wood-Ljungdahl pathway [48]. Gleizer et al. reported *E. coli* bacterium-based ethanol production from CO₂ using isotopic tracer technique and RuBisCO enzyme in an alcohol biosynthesis pathway [49]. Borzyskowski et al. reported *methyl-bacterium extorquens* species-based ethanol production from CO₂ using the 13-C tracer technique and RuBisCO Prk enzyme in a CBB pathway [154]. Maheshwari et al. reported *Bacillus* species SS105-based ethanol production from CO₂ using SDS-PAGE technique and Rbcl, and RuBisCO enzymes in a CBB pathway [116]. Lv et al. reported *Saccharomyces cerevisiae* species-based ethanol production from CO₂ using a gene synthesis technique and XYL2 enzyme in a xylose metabolic pathway [100]. Kopka et al. reported *Synechococcus* species-based ethanol production from CO₂ using a gene cloning technique and CorT enzyme in a CBB and rTCA pathway [86].

Table 4 depicts different bio-products obtained after CO₂ capture, the techniques involved, species utilized, Enzymes or genes involved, and their enzymatic pathway.

6. CO₂ capture and its conversion to syngas

Syngas, short for synthesis gas, is a versatile mixture of gases that is produced through the gasification of organic materials, such as coal, biomass, CO₂, or natural gas. The composition of Syngas typically includes hydrogen, Carbon monoxide, CO₂, and traces of other gases. Syngas is often rich in hydrogen gas, which makes it a valuable feedstock for the production of hydrogen-based fuels and chemicals. CO is another significant component and is crucial for various industrial processes, including the production of synthetic fuels and chemicals. Depending on the feedstock and gasification conditions, Syngas may contain traces of methane. Nitrogen can be present in Syngas, primarily if air is used as the gasification agent.

Syngas is most commonly produced through a process called gasification, in which organic materials such as coal, biomass, or natural gas are used at ambient temperature and definite amounts of O₂ or H₂O (in vapor form) by using gasification agents like O₂, air, or both. This thermochemical process converts the carbonaceous material into a gaseous mixture.

Syngas serves as a crucial precursor for the synthesis of synthetic fuels like SNG, synthetic diesel, and synthetic gasoline through processes like Fischer-Tropsch synthesis. Chemical synthesis is widely used in the synthesis of different chemicals, including methanol, ammonia, and higher hydrocarbons, contributing to the manufacture of plastics,

fertilizers, and other industrial goods. The hydrogen content in Syngas makes it a valuable source for hydrogen production, which is essential for fuel cells and other hydrogen-based technologies. Syngas can be used in gas turbines or engines to generate electricity, providing a clean substitute for fossil fuel.

Syngas is a versatile feedstock that can be utilized in a range of industrial processes for fuel and chemical production. Gasification of biomass or waste materials can convert organic waste into useful energy and chemicals, contributing to waste reduction and resource recovery. Depending on the feedstock used, Syngas production can have lower greenhouse gas emissions compared to direct combustion of the original materials.

While syngas offers many advantages, its production and utilization require careful consideration of feedstock selection, gasification technology, and process optimization to ensure economic viability and environmental sustainability.

Commonly, CCU encompasses several sequential stages, encompassing the capturing, storing, transporting, and converting into useful products [61]. The current cutting-edge CCU process requires significant energy consumption. Currently, there has been a shift towards an ICCU technique. In ICCU, DFMs, comprising both adsorbent and catalytic elements, demonstrate the ability to capture CO₂ from flue gas. Following capture, a reduction was done using H₂ gas to regenerate the DFMs. The incorporation of a catalyst and adsorbent is essential for the efficient utilization of CO₂ [150].

A novel ICCU process is introduced, employing environmentally benign and economically viable calcium carbonate (CaCO₃)-derived calcium oxide (CaO) as a dual-functioning sorbent and an efficient catalyst for the production of highly pure Syngas. This innovative approach significantly diminishes the material expenses associated with ICCU and effectively addresses challenges related to the de-energization of d-block-elements-based deoxygenation catalysts in the orthodox CCU technique. In the capacity of both adsorbent and catalyst, CaO demonstrated noteworthy performance in carbon processing throughput, achieving impressive CO₂ conversion rates exceeding 75%, along with a high yield of carbon monoxide. The substantial influence of reaction temperature on the performance of the ICCU process was also investigated [171]. Elevated temperatures exhibit increased efficacy in carbon monoxide generation, resulting in yields of 0.34, 1.53, and 4.15 millimoles per gram of calcium oxide (CaO) at 600, 650, and 700 °C, respectively over a duration of 28 min. Conversely, the conversion of CO₂ experiences a marginal reduction with escalating reaction temperatures, declining from 88.09% at 600 °C to 75.48% at 700 °C. This phenomenon is attributed to the heightened kinetics of CO₂ desorption. Moreover, CH₄ is not detected throughout the entire conversion process, indicating a complete conversion of CO₂ to CO.

The CO₂ conversion achieved through the ICCU process utilizing CaO in isolation exceeds that of numerous documented CO₂ conversion rates observed in conventional Reverse-Water-Gas Shift reactions (RWGS). These conventional RWGS reactions typically employ transition metal-based catalysts. To corroborate the outstanding efficacy of CaO in ICCU, experiments were conducted substituting H₂ with N₂. Remarkably, the introduction of N₂ does not yield discernible CO production. Intriguingly, the CO₂ yield remains comparable in both nitrogen and hydrogen gas atmospheres during the ICCU [150]. The CO₂ yield stands at 1.35 and 1.54 mmol/g CaO, while the CO yield is observed at 4.15 and 0.01 mmol/g CaO under H₂ and N₂ atmospheres at 700 °C. This observation suggests that CaO functions as a CO₂ adsorbent and acts as a catalyst in the direct reduction of carbonates, facilitated by H₂, leading to CO production. This proposition is substantiated by *in situ* DRIFTS-MS analyses. The mechanism of CO₂ adsorption on calcium oxide and the hydrogen gas-mediated regeneration of calcium carbonate, known as the ICCU mechanism, is also reported. The presence of abundant hydroxyl groups indicates efficient H₂ dissociation on the calcium carbonate surface. Consequently, CO is rapidly liberated from the hydrogenated calcium carbonate. Formate species or

Table 4
Different bio-products obtained after CO₂ capture, techniques involved, species utilized, Enzymes or genes involved, and their enzymatic pathway

Species	Technique	Enzymes/Gene	Pathway	Product	Reference
<i>Pichia pastoris</i> <i>Clostridium carboxidivorans</i>	Genetic manipulation, Isotopic tracer RT-PCR, Fermentation, Homologous and heterogenous expression.	cbbM, groEL, groES Aor, adhE2, fnr	CBB Wood-Ljungdahl pathway, Alcohol biosynthesis	Biomass Ethanol, butanol	Gassler et al. [48] Cheng et al. [23]
<i>E. coli</i>	Metabolic rewiring, isotopic tracer, genetic manipulation	Rubisco, Pfk, CA, FDH	CBB	Biomass	Gleizer et al. [49]
<i>S. elongatus</i> , <i>E. coli</i>	UPLC-MS/MS UPLCMS HPLC Genetic manipulation	PCK MDH Rubisco Pfk Carbonic anhydrase (CA)	PCK pathway CBB	Malate	Hu et al. [69]
<i>Methylobacterium extorquens</i>	13-C-tracer growth phenotyping, LC-MS, Whole-Cell proteomics,	RuBisCO Pfk, ΔftfL, Δgly-A, Δccr	CBB	Biomass	Schada von Borzyskowski et al. [154]
<i>S. elongatus</i>	Metabolic Engg., Flux analyses, Genetic manipulation	PAAS, KDC, Adh, AroGfbr, CA, CcmK1, RuBisCo, CcmM, CcmL, and YqhD	shikimate pathway	Aromatic compound: 2- phenyl ethanol, phenylpyruvate, L-phenylalanine, phenyl-acetaldehyde	Ni et al. [124]
<i>Anabaena PCC7120</i> .	Homologous recombination, Genetic manipulations, GC – MS, qPCR, HPLC	GPP, GDH, YqhD	1,3-propanediol biosynthetic pathway	1,3-Propanediol	Liu et al. [105]
<i>E. coli</i>	Gene cloning, Cas9 Gene knockout, GC, Mass spectrometry, Electrochemical cultivation	FchA, Fold, Fhs, SdaA,	rGCS and RGP	Formate	Tashiro et al. [173]
<i>Acetobacterium woodii</i> , <i>Acinetobacter baylyi</i> <i>Bacillus sp. SS105</i>	Gene Cloning, Biosensor, bio-fluorescence, LC	Acr1, Ramo, Aar, Seado, Pmado, Cer1	Alkane biosynthesis pathways	Alkanes	Lehtinen et al. [95]
<i>Saccharomyces cerevisiae</i>	SDS-PAGE, Enzymatic assay, Gene cloning, GC-MS NMR, FT-IR.	RbdL, CA, RuBisCO	-	Lipids, biodiesel, FAMES	Maheshwari et al. [116]
<i>Synechococcus elongatus</i> <i>PCC 7942</i>	Gene synthesis, gene cloning, fermentation, liquid chromatography, mass spectrometry	XYL1, XYL2, XKS1, sPRK, cfxP1, cbbM, cbbL1-cbbS1, GroEL-GroES, HSP60- HSP10	Xylose metabolic pathway, CBB	Ethanol	Li et al. [100]
<i>Chlorella vulgaris</i>	Metabolic rewiring, gene knockout, gene cloning, enzymatic assay, GC-MS, isotopic tracer, bio fluorescence, metabolomics.	Zwf, Gnd, Pgi, Pfk, Eda, GalP, Edd, RuBisCO, PRK, PFK, ADH, ALDC, ALS	CBB, OPP pathway, ED pathway, EMP, 2,3-BD bio-synthesis pathways	2,3-butanediol	Kassim and Meng [81]
	Genetic Engg., Protoplast preparation, Gene cloning and expression, enhanced green fluorescent protein (EGFP) and Fluorescence, Enzymatic assay, Sodium Dodecyl Sulfate	Fructose 1,6-bisphosphate aldolase	CBB	Lipid	Yang et al. [190]
<i>Synechococcus sp.</i>	Polyacrylamide Gel Electrophoresis (SDS-PAGE)	CorR, CorT, PDC, DsrA, Prbc, ZmpDC, Pyruvate decarboxylase, ADH	CBB, rTCA	Ethanol	Kopka et al. [86]
<i>E. coli</i>	Genetic manipulations, gene cloning, gene expression, LC-MS, GC, enzymatic assay	Prs, Pgi, SerA, Crp, PpsR	rTCA, CBB,	Sugar	Herz et al. [66]
<i>Synechocystis sp. PCC6803</i>	Genetic manipulations, gene cloning, genotyping, Enzymatic assay, Isotope tracer	Malonyl-CoA reductase acetyl- Co-A	3-Hydroxy propanoic acid biosynthetic pathway	3-Hydroxy propanoic acid	Wang et al. [179]
	Genetic manipulations, Overexpression, enzymatic assays, gene knockout, RT-qPCR SDS-PAGE	carboxylase biotinilase NAD(P) transhydrogenase Phosphate acetyltransferase AccA, Mcr, AccB, AccD, PntA, BirA, PhaB			

CBB = Calvin Benson Bassham; HPLC = High Performance Liquid Chromatography; PCK = Phosphoenolpyruvate Carboxy Kinase; RGP = Arg-X-Specific Cysteine Proteinase; RT-PCR = Real-Time Reverse Transcriptase-Polymerase Chain Reaction; UPLC-MS = Ultra High Performance Liquid Chromatography Mass Spectrometry.

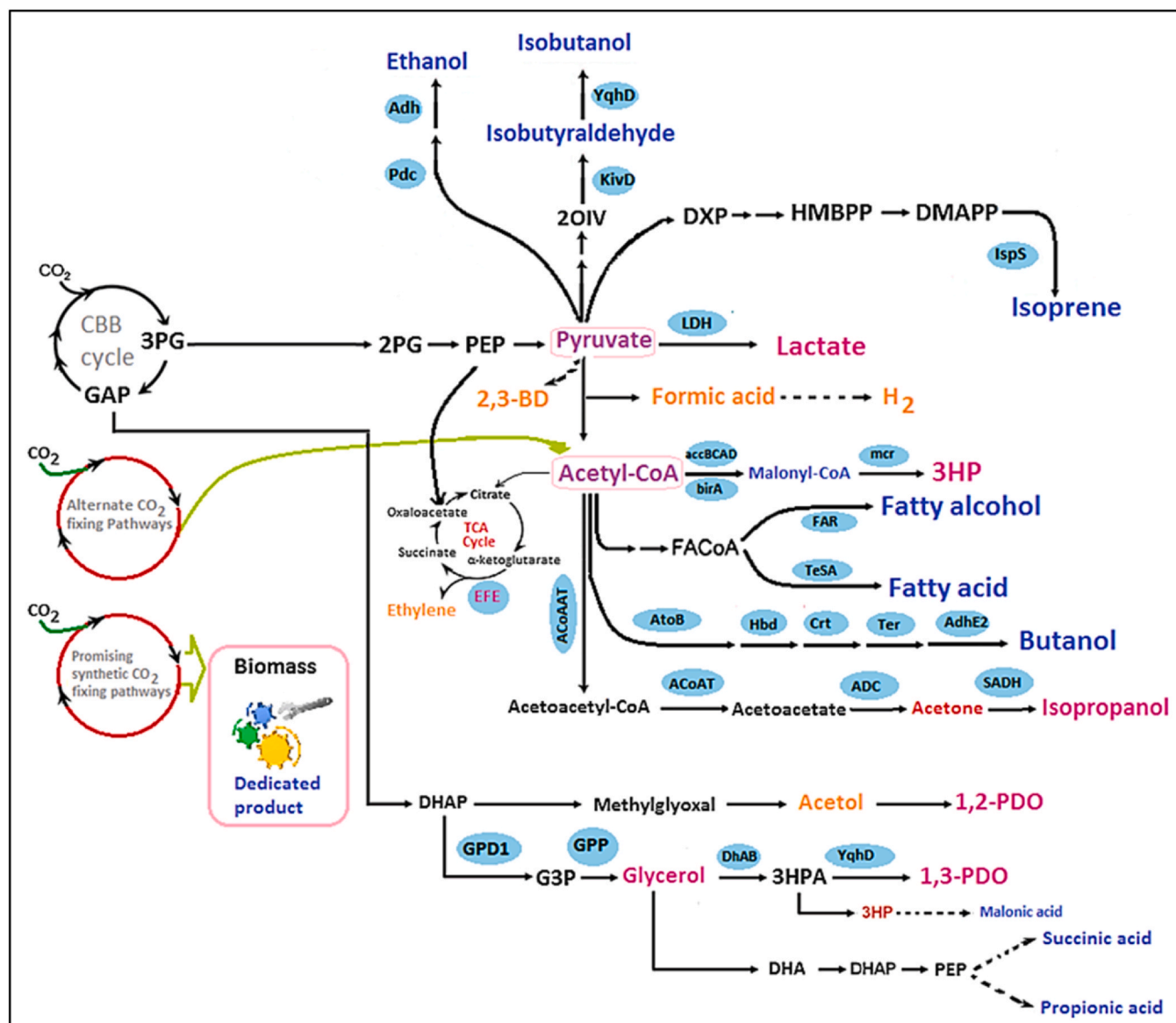


Fig. 4. CO₂ capture and its conversion to bio-fuels and other bio-chemicals. The metabolic process is divided into 2 parts. First is the conversion of the product from CO₂ capture into a metabolic intermediate, that is, Pyruvate/Acetyl-CoA. 2nd is the engineering and linking of a man-made pathway into common intermediates. [Reproduced after getting permission <https://doi.org/10.1016/j.micres.2021.126813>, a copyright of Elsevier].

hydrogenated carbonates are identified as crucial intermediates. Notably, the cost-effectiveness of the employed CaO surpasses that of commonly used d-block metals-based catalytic agents, while maintaining superior CO₂ transformation rates and superb CO selectivity [101]. These findings illustrate the technical and economic merits of the straightforward procedure of CO₂ conversion efficiency, carbon monoxide selectivity, and the utilization of cost-effective and resilient materials. After undergoing 50 cycles of Indirect CCU, the regeneration process of calcium oxide at 855 °C in a hydrogen environment leads to a substantial decline in the CO₂ arrest capacity, decreasing from 12.4 to 2.11 mmol/g CaO. This observed reduction can be attributed to the sintering phenomenon occurring within the CaO particles under the elevated regeneration temperature conditions. Furthermore, an investigation was conducted to assess the kinetic performance associated with both carbonation and H₂ regeneration processes. The carbonation rate, indicative of rapid adsorption, exhibits a decline as the carbonation temperature increases, concurrently prolonging the overall carbonation time. These findings underscore the direct correlation between carbonation kinetics and the efficacy of CO₂ capture, as denoted by the

flue gas per unit of calcium oxide within a given timeframe [56]. In comparison to the carbonation rate, a swifter regeneration process exhibits a stronger correlation with the deactivation of calcium oxide resulting from the rapid volumetric contraction during the transition from calcium carbonate of 37.0 cm³/mol to CaO with 17.0 cm³/mol.

The rejuvenation of CaO in a CO₂ environment appears to be the primary factor contributing to the deactivation of CaO. Shifting the atmosphere from hydrogen to CO₂ at 851 °C leads to notable and expedited deactivation, particularly during the initial 31 cycles. Consequently, the deactivation of CaO may be effectively mitigated through H₂ regeneration. Moreover, regenerating CaO under H₂ preserves the rapid adsorption characteristics of CaO during carbonation and regeneration cycles, offering practical advantages by shortening the carbonation phase [151].

An enhanced ICCU process encompassing CCC and re-adsorption to yield high-purity Syngas from flue gases. The refined ICCU process comprises 3 sequential steps: (i) Employing CaO in isolation for the entrapment of CO₂ from flue gases, thereby mitigating CO₂ emissions, (ii) Utilizing a catalyst composed of CaO and CaCO₃ to recover CaCO₃

and facilitate the CCC into CO by transitioning the gas to H₂, (iii) Employing different Calcium oxide bed as an adsorbent to eliminate unreacted CO₂, resulting in the production of Syngas. The CaO can be recovered similarly by introducing hydrogen gas. Importantly, the absence of additional metal catalysts allows for the repurposing of deactivated CaO in cement manufacturing, thereby averting secondary pollution [202].

This analysis exclusively accounts for material and utility expenses. Notably, the cost of CO₂ avoidance in the Improved CCU technique has diminished from \$271 to \$185 per ton. Furthermore, the energy efficiency, quantified as power generated w.r.t. thermal energy input, exhibits enhancement, increasing from 20.0% to 25.0% when the optimized improved CCU technique is implemented, as opposed to the orthodox CCU, neglecting heat recovery considerations. The noteworthy cost savings in the optimized improved CCU process can be attributed to the economical procurement of materials, reduced expenditures associated with CO₂ storage and transportation, and the intensified nature of the CCU process [141]. Sun et al. empirically validated the viability of an innovative ICCU process designed for the generation of synthesis gas (Syngas) derived from CO₂ sources. This process integrates CO₂ capture and utilization by relying solely on CaO [70]. The innovative concept introduced herein markedly enhances the cyclic stability of calcium oxide (CaO) in terms of Carbon capture while concurrently reducing the overall duration of the CCU process directly from flue gas. Furthermore, we substantiate the merits of generating exclusively pure syngas employing CaO alone, achieved through the integrated CaO carbonation and utilization process, as evidenced by Aspen Plus modeling. The resultant syngas holds potential for application in liquid fuel synthesis, particularly in established processes like Fischer–Tropsch synthesis for commercial fuel production [71]. Fig. 5 illustrates the process of carbon capture and its subsequent utilization in generating Syngas. A comprehensive analysis was done to examine the effect of temperature, cycle rate, and duration on both CO₂ capture and regeneration rates. The investigation utilized an ICCU technique, employing a readily available and cost-effective CaO as a dual-function sorbent and catalyst for the RWGS reaction. The transition of the feed gas from a CO₂ source to hydrogen gas was executed under constant temperature conditions. Remarkably, it was observed that at temperatures changed from 600.0 to 700.0 °C, 75% of the captured CO₂ underwent conversion to CO, achieving a complete conversion rate of 100%. Additionally, the ICCU process significantly improved the cyclic performance of CaO.

7. CCC to CH₃OH

CO₂ and CH₄ stand out as pivotal constituents among atmospheric gases. The noteworthy surge in atmospheric CO₂ levels, primarily attributable to human-induced emissions, poses a formidable peril to the Earth, prompting global warming [192]. In 2018, a substantial emission of 33 Giga-tonnes of CO₂ occurred, resulting in an elevation of atmospheric CO₂ from 281 to 412 parts per million. In response to this issue, 2 potential solutions were introduced: (i) CCS, notable for its economic viability challenges as it lacks profitability, and (ii) CCU, aiming to convert waste CO₂ into valued products like hydrocarbons and biofuels. Different techniques presently in use are the transformation of CO₂ into value-added products, by CO₂ hydrogenation, reduction (photo-chemical), and photo-electrochemical process.

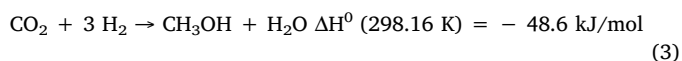
Specifically, targeted research has been proposed by Studt et al. to explore the catalytic hydrogenation of CO₂ into CH₃OH, a process considered both widely utilized and straightforward in its application. They addressed the environmental concern posed by elevated CO₂ levels and explored sustainable approaches for transforming CO₂ emissions into useful organic products [166]. CO₂ hydrogenation yields different organic products, like methanol, which is particularly noteworthy due to its dual significance as a green energy source and a versatile precursor for the synthesis of diverse chemical compounds

[166]. Methanol serves as a viable energy source due to its liquid state at ambient temperatures, facilitating convenient transportation and storage. Approximately 85.0% of CH₃OH finds application in industrial chemistry, primarily serving as a solvent or as a crucial reagent for synthesizing HCHO and CH₃COOH.

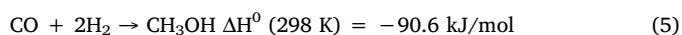
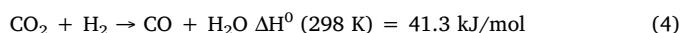
In the early 1920s, the Baden Aniline and Soda Factory (BASF) achieved successful methanol production from Syngas during NH₃ synthesis, utilizing the ZnO–Cr₂O₃ catalyst and temperatures ranging from 320.0 to 450.0 °C and pressures between 250 and 350 atm. Subsequently, in the 1961s, the Imperial Chemical Industry (ICI) pioneered a methanol synthesis route wherein Syngas, enriched with a substantial CO₂ fraction, underwent a highly selective reaction catalyzed by Copper and Zinc oxide catalysts. This development introduced the first commercially established Cu/ZnO/Al₂O₃ catalyst [136].

Presently, this material stands as the prevailing substrate for effecting the conversion of CO₂ into CH₃OH. This preference arises from the inherent advantages of heterogeneous catalysts over homogeneous systems, specifically attributable to their heightened stability and facile usability.

The 1st step is the manufacture of CH₃OH from CO₂ and H₂:



RWGS reaction is the 2nd step, which generates CO:



Eqs. (3) and (5) demonstrate, (following Le Chatelier's principle), that at elevated pressures and reduced temperatures favor the reaction towards methanol production (Eq. 5), rather than the generation of carbon monoxide (Eq. 4). Consequently, the catalytic hydrogenation of CO₂ into CH₃OH may proceed either indirectly or directly [73].

Out of the 92 naturally occurring elements found on Earth, Copper holds the position as the 25th most abundant, rendering its utilization in catalysis. In the preparation of CH₃OH via the hydrogenation of CO and CO₂, particular emphasis is directed towards Cu metal serving as the active phase, complemented by ZnO. The noteworthy metal dissolution and stability exhibited by the commercial Copper/Zinc Oxide/Al₂O₃ catalyst can be attributed to the distinctive microstructure attained post-reduction. In this configuration, ZnO NPs serve as spacers between CuO particles, with Al₂O₃ contributing to enhanced thermal and chemical stability. The operating pressure for CH₃OH synthesis has been significantly reduced to a range of 50.0–100.0 bar while maintaining a commendable methanol selectivity of 50.0% [17]. Bimetallic catalysts (Cu/ZnO) have garnered significance as a pivotal catalyst category, owing to their distinctive attributes that amalgamate the properties of constituent metals. This amalgamation induces alterations in the adsorption characteristics of metal surfaces, thereby augmenting catalytic efficiency. Beyond the Copper-Zinc-based system, diverse bimetallic systems, including but not limited to Palladium-Zinc, Palladium-Gallium, Copper-Nickel, and Gallium-Nickel, have undergone scrutiny. Notably, investigations reveal that a Pd-Zn-based catalyst exhibits enhanced favorability for methanol production. The Palladium-Zinc surface manifests a remarkably elevated kinetic energy for the RWGS reaction, thereby effectively promoting CH₃OH synthesis while mitigating CO concentrations, particularly under low pressure (20 bar) [85].

The investigation revealed that the catalytic properties of the Ni-Ga system surpasses that of the commercial Cu/ZnO/Al₂O₃ catalyst, leading to reduced CO production. This highlights the potential of bimetallic catalytic systems in addressing challenges associated with high-pressure conditions and low selectivity towards methanol in relation to CO. Notably, the Cu-Zn bimetallic system demonstrates economic advantages and widespread utilization. Beyond concerns of high pressure and low selectivity, there is an additional challenge related to achieving a high catalytic yield [30].

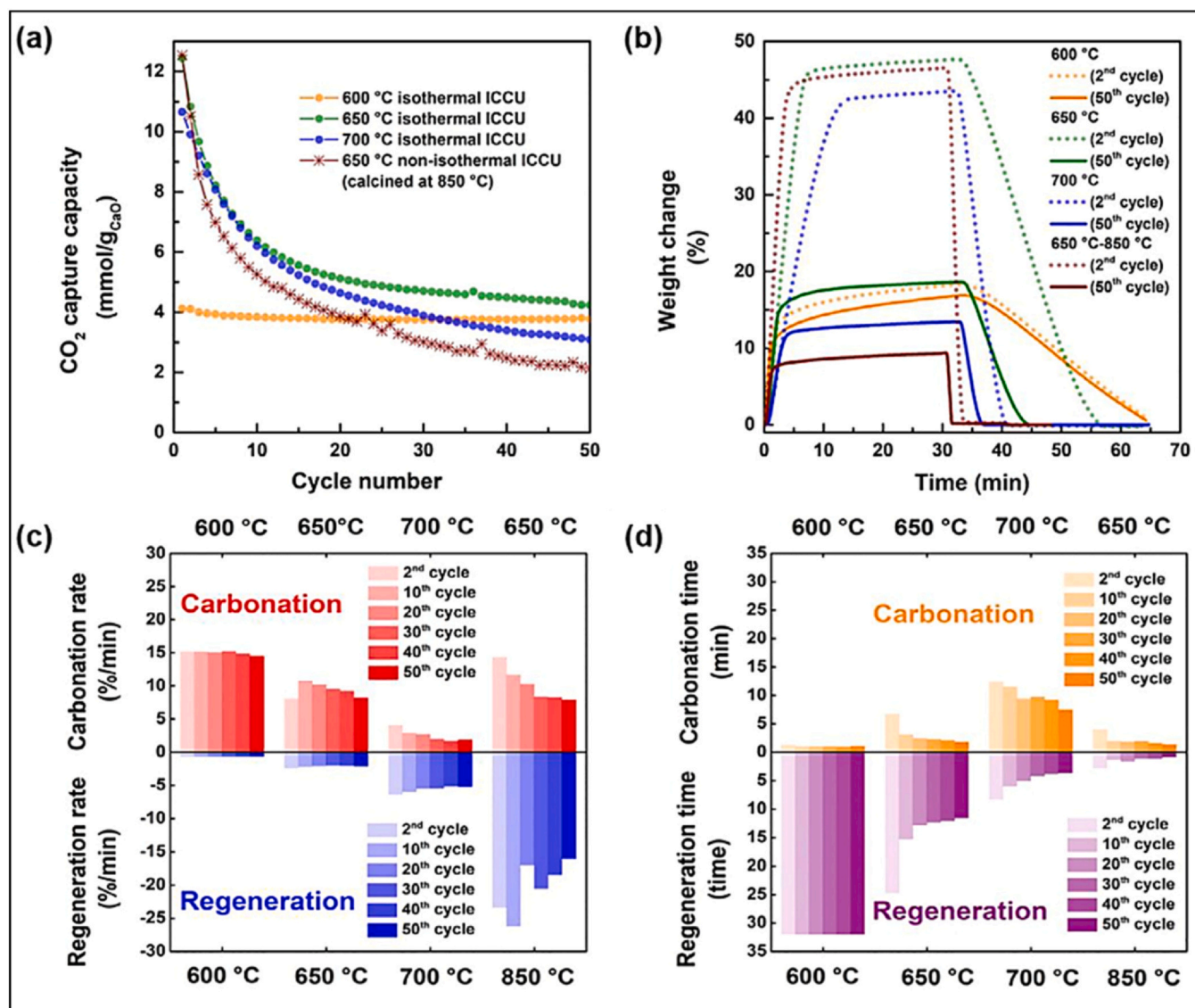


Fig. 5. CCU for the liberation of Syngas. CO₂ capture capacity versus cycle number in isothermal (600 – 700.0 °C) and non-isothermal condition (651.0 °C) and regenerated at 851.0 °C (a), Weight change versus time (Dynamic profile of second and fiftieth cycle) (b), Comparative study of regeneration and carbonatation rate (% min) during different cycles at different temperatures (c), Comparison of regeneration and carbonatation time (min.) in different cycles (d). [Reproduced after obtaining permission Ref. [101] <https://doi.org/10.1016/j.cscst.2021.100001>]. CCU = Carbon Capture and Utilization.

Capping agents play a pivotal role as stabilizing agents, impeding the excessive growth of NPs and their aggregation. The primary objective in employing a capping agent is to attain the lowest possible NPs, thereby maximizing the surface area-to-volume ratio [138]. The capping agents reported were poly vinyl pyrrolidone (PVP) and Na₃C₆H₅O₇ (Sodium citrate). The investigation primarily centered on Zeolite, Activated Carbon (AC), and PPy nanotubes. AC, characterized by a highly porous carbonaceous structure with micro- and mesoporosity, is extensively utilized for adsorption applications. Both materials demonstrate notable adsorption capacities across a broad spectrum of gas molecules, including CO₂. PPy nanotubes encompass CNTs with N incorporation, achieving high CO₂ conversion efficiency at high temperatures [34]. The inclusion of N atoms in PPy and its carbonized derivatives exerts a favorable influence on their catalytic attributes, both in solitary utilization and as substrates for MO NPs. The electron pair associated with N atoms actively engages in desorption/adsorption processes of products and reactants critical for achieving enhanced catalytic efficiency. Despite the notable electrical conductivity of PPy nanotubes, they focused on investigating this material stems from the inherent challenges in directly applying bimetallic NPs. The difficulty

arises from their pronounced inclination towards agglomeration owing to their nanoscale dimensions and the Van der Waals bondings occurring between the metallic components.

The CH₃OH selectivity of the PPy/CNT/N based catalysts was investigated across a temperature range of 180–280 °C. Remarkably, at temperatures ranging from 180 to 220 °C, a consistent 100% methanol selectivity was observed for all catalysts, indicative of the absence of CO production within this temperature range. However, beyond 220 °C, a decline in methanol selectivity was noted, reflecting a reduction in the catalysts' efficiency. Notably, at °C, nearly all catalysts exhibited 100% methanol selectivity; nevertheless, a general decrease in selectivity was observed as the temperature increased. This decline in selectivity can be attributed to the negative standard enthalpy of the methanol reaction, signifying its exothermic nature and preference for lower temperatures. Chinchin et al., [24]. In the investigation, it was observed that, until reaching 280 °C, no detectable amounts of CO were produced by 3 distinct catalysts: ZnO with and without PVP, and Copper/Zinc oxide with PVP. The catalytic performance and methanol selectivity exhibited a discernible correlation with the augmentation of ZnO NPs concentration. Notably, an increased ZnO NPs content in the catalyst was

found to enhance both catalytic activity and methanol selectivity. This improvement stemmed from 2 key factors: enhanced interactions between Cu and ZnO, fostering CO₂ hydrogenation, and the suppression of the RWGS reaction, responsible for CO production. Further investigation revealed that the absence of CO in materials synthesized using PVP might be attributed to the suboptimal dispersal of Zinc oxide and agglomeration of Copper NPs. As anticipated, active sites of Cu NPs were rendered inactive due to formate poisoning, leaving only the active sites of ZnO accessible for catalytic reactions [52].

Various Cu and Zn compounds, including single metals and bimetallic materials, were successfully synthesized. These materials were either embedded or not embedded in diverse support structures. The catalytic efficacy of these synthesized compounds was subsequently investigated and reported [113]. Overall, bimetallic materials exhibited superior efficacy compared to their single-metal counterparts in terms of CH₃OH production. This architectural arrangement substantially enhanced their catalytic performance [47]. The introduction of PVP as a capping agent exhibited enhanced catalytic efficacy in the context of single-metal NPs, attributed to its role in promoting the formation of more uniform and small-size particles. However, the inclusion of PVP impeded the proper homogenization of both metals, resulting in a discernible inclination toward agglomeration and a subsequent reduction in catalytic efficiency. The significance of employing a supporting matrix was underscored by utilizing nanotubes to increase the separation between active sites or employing porous supports like Zeolite or AC. These supporting structures proved instrumental in enhancing the adsorption of CO. Consequently, these dual attributes of porous supports distinctly contribute to the augmented catalytic efficiency of the NCs in comparison to other materials reported in the literature [156]. Table 5 depicts the different methods involved, the catalyst used, and the temperature of CO₂ capture and its conversion to CH₃OH [4,27,54,55,75,103,106,111,142,159,160,175,176]. A 99.5% methanol production was achieved using Cu/Ga/Zn/SiO₂ catalyst in the co-impregnation method [175]. A 100.0% methanol production was achieved using Cu/Zn/ZrO₂ catalyst in the co-precipitation method [159]. A 97.0% methanol production efficiency was reported using Ag/Zn/ZrO₂ catalyst in the co-precipitation method [159].

Fig. 6 depicts different mechanisms of CO₂ capture and conversion to CH₃OH. Potential energy surface for the reduction of CO₂ to CH₃OH by NH₃-B₂H₆ (A), The process for the Pyridine initiated reduction of carbon dioxide to the different product like HCOOH, HCHO, and CH₃OH (b) Photocatalytic reduction of CO₂ on Copper/Titanium oxide (c), and Graphical representation of electrolytic cell for generating CO + H₂ (Syn gas) by the reduction of carbon dioxide and H₂O (d).

Table 5

The method involved, the catalyst used, and the temperature of CO₂ capture and its conversion to methanol

Method involved	Catalyst used	Temperature (°C)	CO ₂ Conversion efficiency (%)	Methanol production (%)	Reference
Co-impregnation	Cu/Ga/Zn/SiO ₂	271	5.6	99.5	Toyir et al. [175]
Co-impregnation	Ga/Cu/ ZnO	271	6.0	88.0	Toyir et al. [176]
Precipitation/deposition	ZrO ₂ /Cu	241	6.3	48.8	Liu et al. [106]
Precipitation/deposition	Ga/Cu/ ZrO ₂	251	13.7	75.5	Liu et al. [111]
Precipitation/deposition	B/Cu/ZrO ₂	251	15.8	67.2	Liu et al. [111]
Coprecipitation	Ga/Cu/Zn/ ZrO ₂	251	NR	75.0	Stoczyński et al. [160]
Coprecipitation	Zn/Cu/ ZrO ₂	250	19.4	29.3	Raudaskoski et al. [142]
Combustion of Urea-Nitrate	Cu/Zn/ZrO ₂	240	17.0	56.2	Stoczyński et al. [159]
Coprecipitation	Cu/Zn/ZrO ₂	220	21.0	68.0	Stoczyński et al. [159]
Combustion of Glycine-Nitrate	Cu/Zn/ZrO ₂	220	12.0	71.1	Guo et al. [54]
Coprecipitation	Cu/Zn/Al/ZrO ₂	240	18.7	47.2	An et al. [4]
Coprecipitation	Ag/Zn/ZrO ₂	220	2.0	97.0	Stoczyński et al. [159]
Coprecipitation	Au/Zn/ZrO ₂	220	1.5	100.0	
Incipient wetness	Pd/Zn/ZrO ₂	250	6.3	99.6	Liang et al. [103]
Incipient wetness	Ga ₂ O ₃ /Pd/SiO ₂	250	NR	70.0	Collins et al. [27]
Sol-Gel	LaCr _{0.5} Cu _{0.5} O ₃	250	10.4	90.8	Jia et al. [75]

8. CCC to cyclic carbonates

Cyclic carbonates (CCs) are a class of organic compounds characterized by a ring structure containing one or more carbonate groups. The carbonate group consists of a central C-atom bonded to 3 O-atoms. The cyclic nature of these compounds makes them interesting in various industrial applications, particularly in green chemistry and sustainable materials. CCs are regarded as cyclic arrangements of carbonate units. The simplest CCs is ethylene carbonate, which has a 5-membered ring containing one carbonate group. Other examples include propylene carbonate, trimethylene carbonate, and larger cyclic carbonates with multiple carbonate units in the ring.

CCs can be synthesized through different methods, often involving the reaction of epoxides (oxiranes) with CO₂. This reaction, known as the cyclic addition of carbon dioxide to epoxides, can be catalyzed by different catalysts, including metallic complexes. The choice of catalyst and reaction conditions can influence the selectivity and efficiency of the CCs synthesis.

CCs are essential intermediates in the synthesis of polycarbonates. Polycarbonates are high-performance plastics with applications in eyewear, electronics, and automotive components. Some CCs, like propylene carbonate, are considered green solvents due to their low toxicity and biodegradability. They find applications in various industries as eco-friendly alternatives to traditional solvents. CCs are used as components in electrolytes for rechargeable batteries. They improve the working and safety of the rechargeable batteries by enhancing the stability of the electrolyte.

CCs have been investigated for their potential use in CCS processes. They can combine with CO₂ to form stable carbonates, aiding in the capture and storage of CO₂ emissions. CC can undergo polymerization reactions to form polymeric materials with different properties. These polymers find applications in coatings, adhesives, and other industrial processes. The synthesis of CCs from epoxides and CO₂ is considered a more environmentally friendly process compared to traditional methods, offering a sustainable alternative. Some CCs, especially those used as green solvents, are biodegradable, contributing to reduced environmental impact. CCs exhibit versatility in terms of their applications, ranging from polymer production to electrolytes in advanced batteries.

In a nutshell, CCs represent a class of compounds with diverse applications, particularly in the development of sustainable materials and processes. Their unique structure and properties make them valuable in various industries seeking greener alternatives and more environmentally friendly solutions.

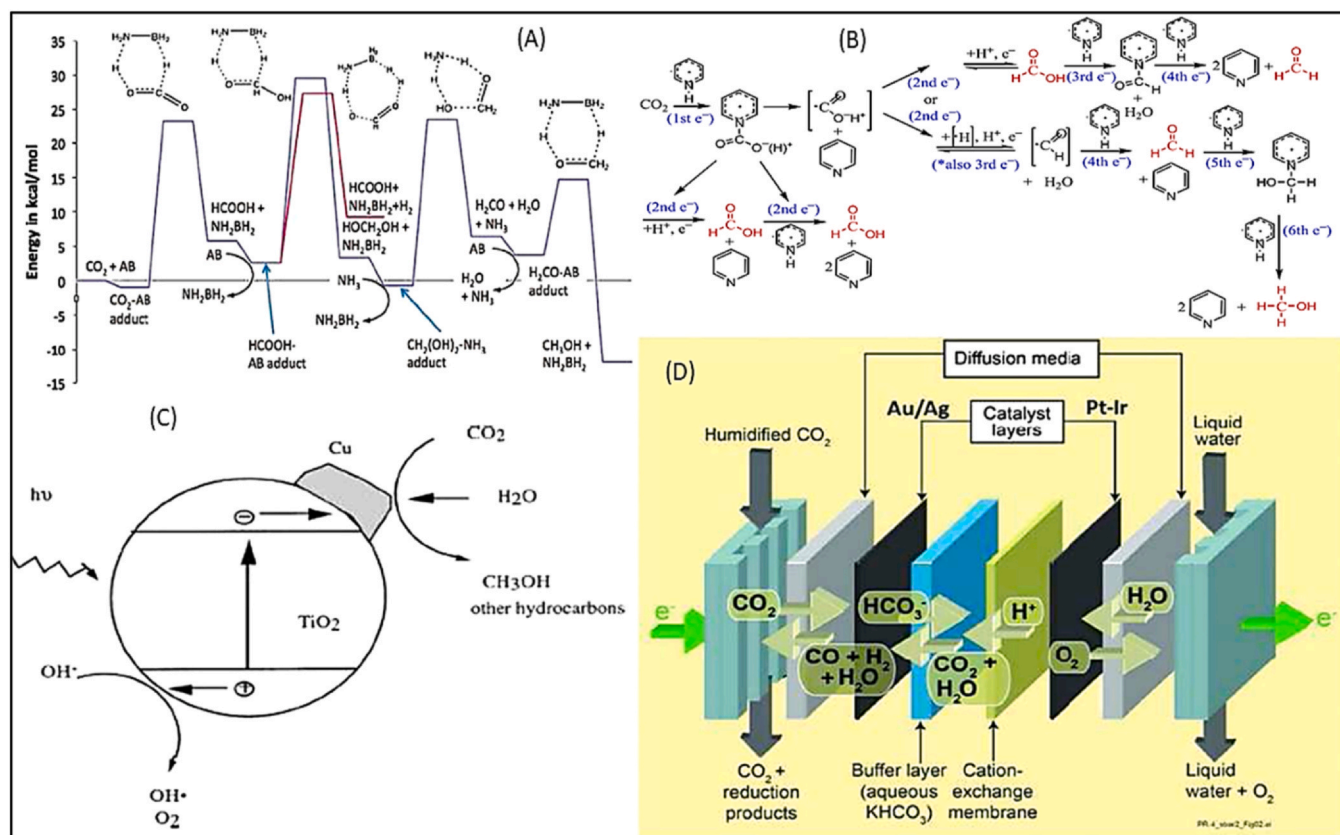


Fig. 6. Different mechanisms of CCC to CH₃OH. Potential energy surface for the reduction of CO₂ to CH₃OH by NH₃-B₂H₆ (A), The proposed process for the Pyridine catalyzed reduction of carbon dioxide to different products of HCOOH, HCHO, and CH₃OH (b), Photocatalytic reduction of CO₂ on Copper/Tin oxide (c), and Graphical scheme of an electrolytic cell for generating CO + H₂ (Syn gas) by reduction of carbon dioxide and water (d). [Reproduced after getting permission, Ref. Ganesh [46] <http://dx.doi.org/10.1016/j.rser.2013.11.045>]. CCC = Carbon Capture and Conversion.

The CCC in value-added products holds paramount significance in the context of optimizing CO₂ resource utilization. This is underscored by the abundant, non-toxic, cost-effective, and renewable nature of CO₂, positioning it as a valuable C1 feedstock [10,109,122,133,158,200]. Within the spectrum of frequently documented CCC methodologies, the amalgamation of CO₂ with epoxides, resulting in the formation of CCs, manifests a noteworthy 100% atom economy and represents a sustainable process. These cyclic carbonates exhibit versatile utility in the synthesis of refined chemicals, polymers, biofuels, pharmaceutical products, and environmentally friendly electrolytes designed for rechargeable batteries [3,6,18,38,51,83,123,129,148]. An economically viable and highly efficient catalytic conversion plays a vital role in the capture and utilization of CO₂. Given the relatively inert nature of CO₂, the reaction necessitates the involvement of a catalyst for facilitation. Different efficient catalysts have been suggested, encompassing both homogeneous and heterogeneous catalytic systems, such as organocatalysts [16,42,53,137,196], ionic liquids [97,102,170,180,181], metal complexes [31,32,78,119], MOFs [107,117,135,140], Covalent-Organic Frameworks (COFs) [44,113,132], functional polymers [72,113,155], etc. The intricate preparation process, characterized by numerous synthetic pathways and stringent conditions, imposes limitations on the potential applications of these materials. Recently, C-based materials (AC), particularly those derived from Graphene and Graphitic CN, have exhibited promising catalytic properties in the context of CO₂ fixation to cyclic carbonates [1,19,67,90–92];[104,118,152,167];[184–186,198]. Surface functional groups, including hydroxyl, acids, and amines, are present on Carbon-based materials following modification. These functional groups serve as effective activation sites, facilitating interactions with epoxides. To attain elevated catalytic activity, meticulous modifications like doping with heteroatoms (Boron, Nitrogen, Sulfur, and Phosphorus), and

Co-catalyst fixing remain essential [1,19,50,67,90–92];[104,118,152,167];[183–186,198,x205].

The rigorous conditions involved in the preparation and alteration of catalysts, intricate fabrication of Co-catalysts, elevated reaction temperatures, and substantial CO₂ pressures present notable challenges in the domain of CO₂ conversion. Hence, there is a compelling need for the innovation of novel catalysts that exhibit facile preparation, manifest high reactivity under optimum conditions, and demonstrate commendable recyclability. Carbon dots (CDs), initially identified in 2004, represent a promising avenue for addressing these challenges [187], are a novel class of Carbon-based nanomaterials, characterized by specific dimensions and functional groups, has been identified. These Carbon-based nanomaterials, referred to as CDs, exhibit the capability to serve as hydrogen-bond donors. This property renders them suitable for activating epoxides, thereby demonstrating potential efficacy in catalyzing the cyclic addition between CO₂ and epoxides.

A nano-scale heterogeneous catalyst utilizing CDs was developed via a one-pot hydrothermal method. The catalyst incorporates biomass-derived sodium phytate (SP), cost-effective polyethyleneimine (PEI), and the co-catalyst KI. The CD-based catalyst demonstrates promising attributes in terms of availability and affordability [108]. Hydrogen bonding facilitates the activation of epoxides, while nitrogen (N) provided by polyethyleneimine (PEI) serves as a source for CO₂ fixation. Additionally, the co-catalytic influence of potassium iodide (KI) is integrated into a single CDs catalyst, exemplifying a versatile "all-in-one" functionality. This consolidated CDs-catalyzed cyclic addition of CO₂ to epoxides demonstrates exceptional catalytic efficiency and robust functional group acceptance. This transformative process converts epoxides into cyclic carbonates under optimum conditions characterized

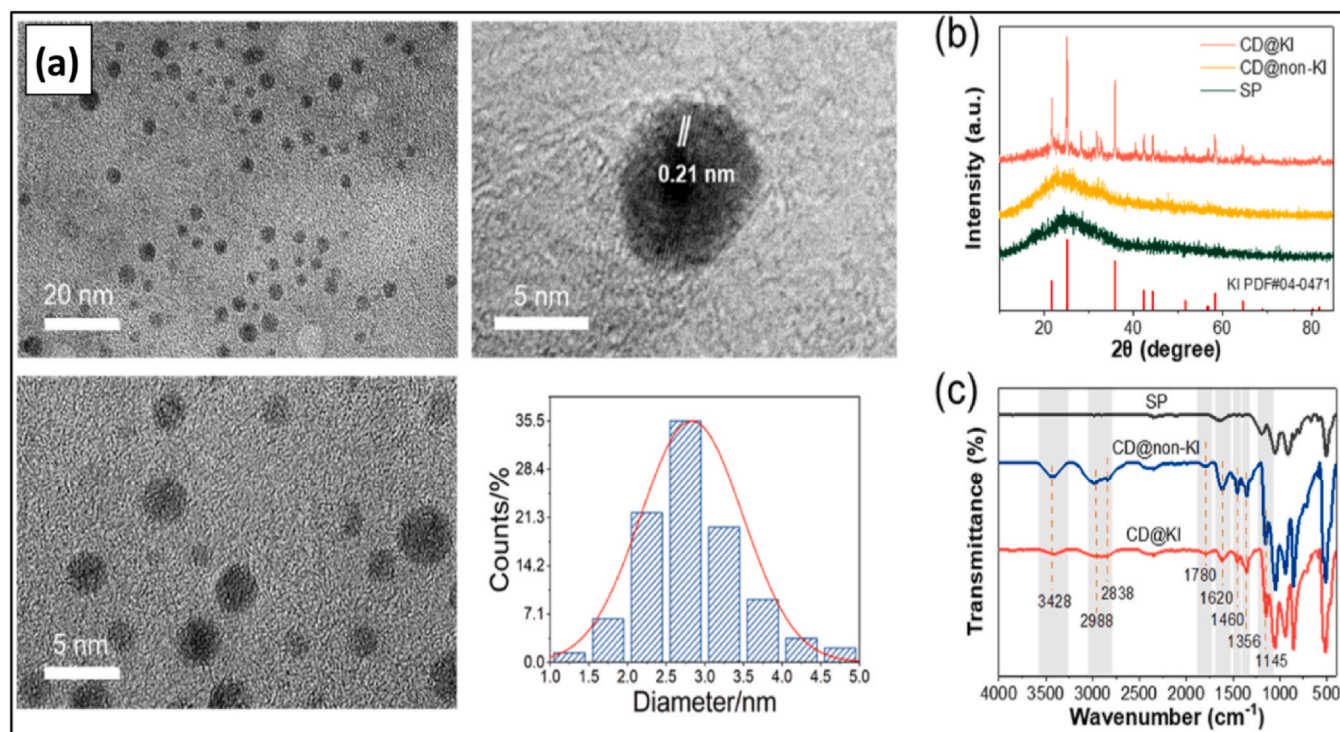


Fig. 7. (a) TEM optical image of CD/KI, (b) X-ray diffraction of CD@KI. (c) FTIR absorption peak of SP, CD@non-KI, and CD@KI, respectively. [Reproduced after getting permission <https://doi.org/10.1016/j.carbon.2023.118118>]. TEM = tunneling electron microscope.

by low pressure (1.0 atm), a solvent-free environment, and temperatures i.e., 80.0 °C to 100.0 °C. Fig. 7 depicts a TEM optical image of CD/KI, (b) an X-ray diffraction of CD/KI. (c) Fourier Transform Infrared Spectroscopy (FTIR) absorption peaks of SP, CD@non-KI, and CD@KI, respectively. The size of the CD was less than 10 nm (Fig. 7a). The XRD pattern of Sodium phytate (SP) and CD without KI are amorphous (Fig. 7b). Introducing KI into CD increases the crystallinity in the composite (Fig. 7b). FTIR spectra of pure SP show an absorption band only in the fingerprint region of the spectrum. FTIR spectrum of pure CD without KI shows absorption spectra in both functional and Fingerprint regions of IR spectrum (Fig. 7c). The number of signals in the Fingerprint region upsurges after the addition of KI in CDs. These may be due to an increase in crystallinity in composite and same information is also observed from XRD pattern of CDs.

Fig. 8 depicts different applications for polyhydroxy urethane (PHU) preparation and their optical activities. Preparation of PHU from epoxides following cycloaddition of CO₂ and polymerization using alkyl amine in the presence of CD/KI. FTIR spectra of CDs with and without PHU and cyclic carbonates are also shown in Fig. 8(a). Optical images of CDs with and without PHU on UV excitation and switched off UV lamp (b). Phosphorescence and Fluorescence bands of CDs (c). Phosphorescence lifetime i.e., number of counts versus time of CDs (d). Fig. 8 depicts different ligands used as capping agents for metal nanoparticles and the formation of cyclic carbonates. Table 6 depicts different types of substrate support used, types of linkers, and products formed after CO₂ capture by different types of adsorbents (Fig. 9. depicts different ligands used as capping agents for metal nanoparticles and formation of cyclic carbonates.

Fig. 10 shows a timeline of CO₂ capture and its conversion into useful products. From the 1970s to the 1980s, conceptual work began on CO₂ utilization to address rising CO₂ levels. Initial efforts in the 1970s focused on carboxylation reactions and urea production (e.g., urea from CO₂ and NH₃). In the 1990s, Advances in organometallic catalysis for CO₂ activation began. CO₂ was utilized to synthesize cyclic carbonates (important for polymers and solvents). In the 2000s, catalytic pathways started. A stronger focus was on catalytic hydrogenation

of CO₂ to CH₃OH and other C₁ chemicals. In 2010–2015, the discovery of efficient catalysts for CO₂-to-methanol, CO₂-to-olefins, and CO₂-to-CO conversion took place. In the 2016–2020s, electrochemical cells capable of selective CO₂ conversion to multicarbon products (C₂, C₃ molecules) were developed. Companies like Covestro produce polycarbonate polyols using CO₂ feedstock. From the 2020s to the present day, highly selective catalysts have been developed for CO₂-to-ethylene, propylene, and even higher alcohols. New photoelectrochemical systems that mimic plant photosynthesis were developed. Fig. 11 depicts CO₂ capture and its conversion to ethanol, Syn gas, Biofuel, Cyclic carbonates, methanol, and methane.

The conversion of CO₂ into valuable chemicals and fuels like methane, methanol, ethanol, syngas, and cyclic carbonates has emerged as a promising approach to mitigate greenhouse gas emissions while enabling a sustainable carbon economy. However, these transformations involve complex reaction mechanisms that are strongly influenced by the nature of the catalyst, reaction environment, and process thermodynamics. Each conversion pathway follows distinct reaction intermediates and transition states, with varying degrees of experimental validation and theoretical prediction. For example, the Sabatier reaction for CO₂ methanation proceeds through adsorbed CO intermediates and hydrogenation steps, whereas methanol and ethanol synthesis typically involves *formate* and *carboxylate* intermediates whose stabilities depend on catalyst composition and surface morphology. Similarly, cyclic carbonate formation through CO₂-epoxide coupling is thermodynamically favorable yet kinetically hindered without suitable co-catalysts.

Understanding these kinetic and thermodynamic limitations, along with identifying the rate-determining steps, is essential to rationally design catalysts and optimize reaction conditions for efficient CO₂ valorization. The present review critically examines the mechanistic pathways of major CO₂ conversion routes, highlighting the interplay between experimental evidence and theoretical insights that guide the development of next-generation catalytic systems for carbon utilization.

Although different studies report the economic potential of CO₂ capture and utilization pathways, typically estimated costs of US

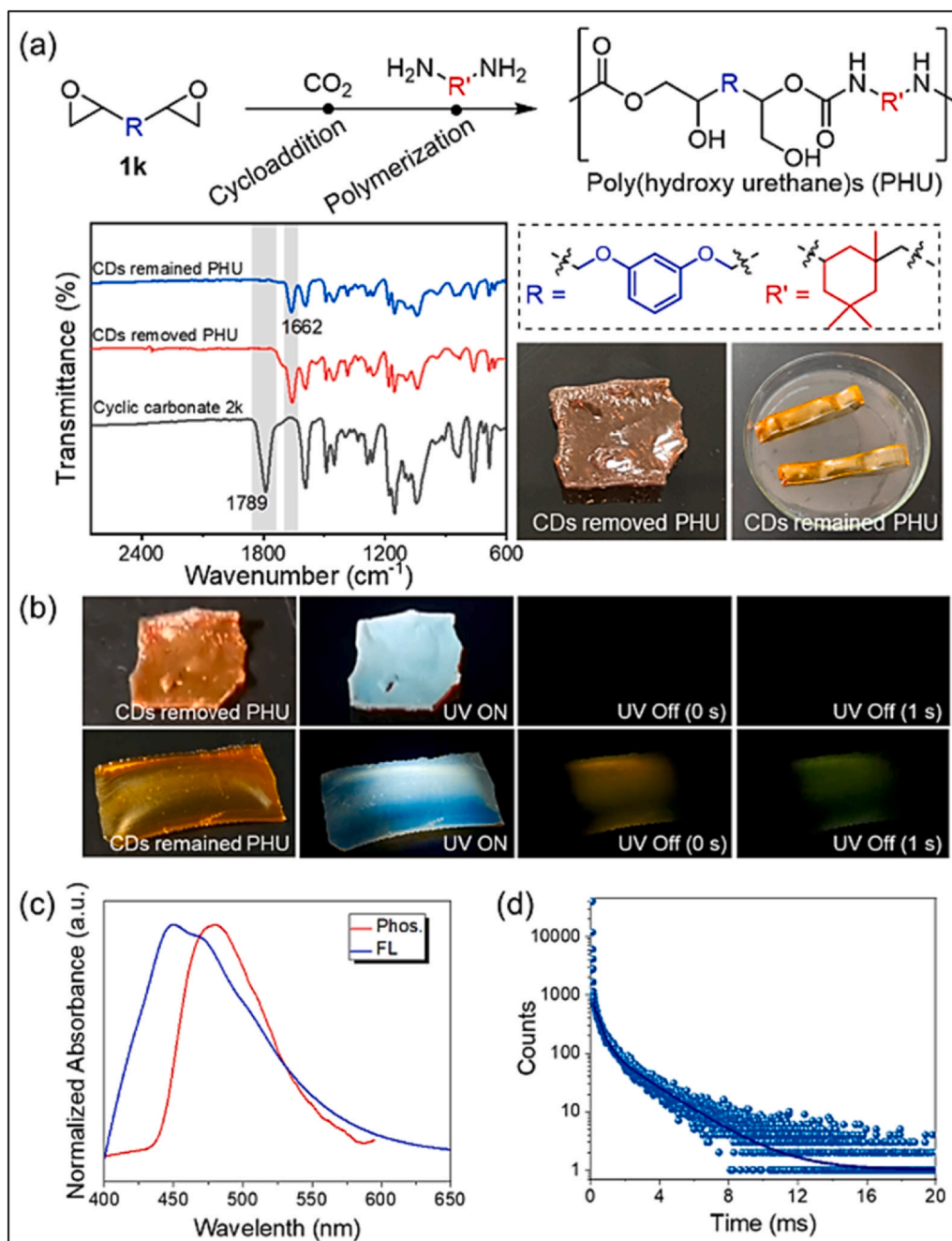


Fig. 8. PHU preparation and their optical activities. (a) Preparation of PHU from epoxides using CD@KI. (b) Optical images of CDs with and without PHU upon UV exposure and switched off UV lamp. (c) Phosphorescence and Fluorescence signals of CDs. (d) Phosphorescence (number of counts versus time) lifetime of CDs. [Reproduced after getting permission <https://doi.org/10.1016/j.carbon.2023.118118>]. PHU = Polyhydroxy Urethane.

Table 6

Epoxide substrate support used, type of linker, and product formed after CO₂ capture by different types of adsorbents

Substrate for CO ₂ capture	Types of linkers used	Product formed	Reference
Homogenous catalyst-based quaternary ammonium salts	Epoxides	Cyclic carbonates	Srivastava et al. [165]
Ionic liquids	Epoxides	Cyclic carbonates	Chen et al. [21]
MoFs	Epoxides	Cyclic carbonates	Pal; Sumida et al. [134,169]
Amino functionalized MoFs	Epoxides	Cyclic carbonates	Lu et al. [112]
MoFs/Bu ₄ NBr	Epoxides	Cyclic carbonates	Song et al. [162]
Zn/MoFs in the presence of TBAB as a cocatalyst	Epoxides	Cyclic carbonates	Zhou et al. [203]
CuL(ClO ₄) ₂ /Zr ₆	Epoxides	Cyclic carbonates	Han et al. [59]
Cu(II)-MoFs + Tetra carboxylate ligand	Epoxides	Cyclic carbonates	Li et al. [98]
Zr-metallo porphyrinic + TBAB as a cocatalyst	Epoxides	Cyclic carbonates	He et al. [64]
[(CH ₃) ₂ NH ₂] [Zn ₂ L(H ₂ O)PO ₄] ₂ DMFs using dicarboxylate ligand (H ₂ L)	Epoxides	Cyclic carbonates	Gupta et al. [57]
Zr ₆ Cluster + [Cu(cyclam)] ²⁺	Epoxides	Cyclic carbonates	Zhu et al. [206]

TBAB stands for Tetrabutyl Ammonium bromide, and Cyclam stands for [1, 4, 8, 11-tetra aza cyclo tetradecane].

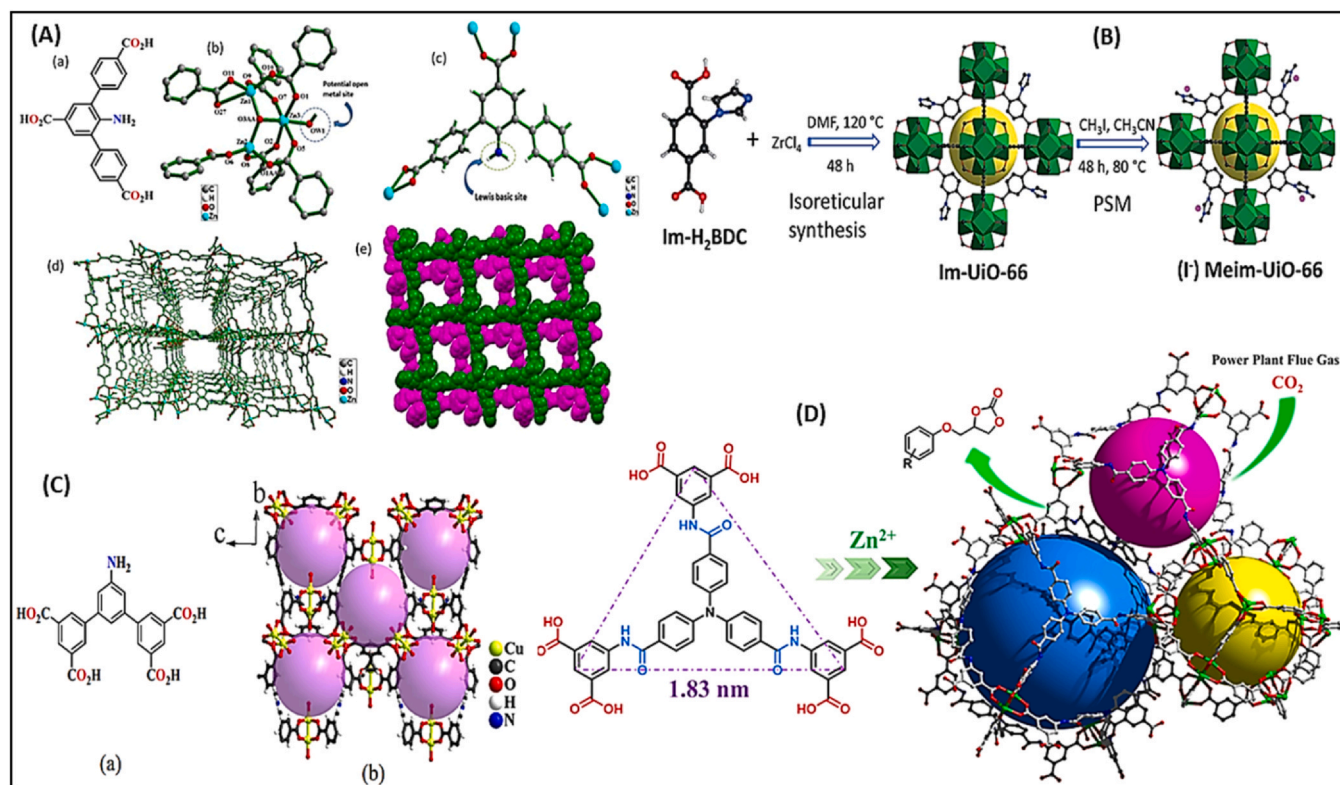


Fig. 9. Different ligands used as capping agents for metal nanoparticles and formation of cyclic carbonates. Tetracarboxylate ligand and separate water and Zinc metal bound Secondary building Units (SBUs) and before and after interpenetration into MOFs framework structure (A), Im-H2-BDC ligand coordinated with Zr metal after isorecticular synthesis yield Im-10-66A complex which on further reaction with CH_3I and CH_3CN to form Iodide salt of Meim-UiO-66 cyclic carbonates (B), bent shape tetracarboxylate ligand having NH_2 group in the center acting agent for Cu metal helping in entrapment of CO_2 molecules with an amine group (C), Acrylamide based ligand that is nitrile-tris(benzoyl)tris(azanediyl)triiso phthalic acid (NTTA) coordinated with Zn and Cu metal for CO_2 capture (D). [Reproduced after getting permission from Ref. [159] <https://doi.org/10.1016/j.ccr.2019.213173> copyright of Elsevier].

\$50–250 per ton of CO₂ avoided depending on the technology and energy source. In practice, real-world demonstration projects reveal a broader range of techno-economic outcomes due to variations in scale, feedstock purity, and integration with renewable energy systems. For example, Carbon Recycling International's CO₂-to-methanol plant in Iceland reports production costs of US\$150–200 per ton CO₂ converted, while CarbFix's mineral carbonation process achieves permanent CO₂ sequestration at US\$25–30 per ton under favorable geological conditions. Similarly, Sunfire's CO₂-to-syngas project demonstrates the influence of renewable electricity prices on overall economic feasibility, with payback periods extending from 8 to 15 years depending on energy tariffs and carbon credit values.

To better capture these techno-economic dynamics, a sensitivity analysis was conducted considering key cost drivers such as electricity price, CO₂ capture efficiency, hydrogen production cost, and policy incentives. The results indicate that process economics are most sensitive to the cost of green hydrogen and renewable power availability, highlighting the importance of coupling CO₂ utilization technologies with low-cost renewable energy sources and supportive carbon policies. These insights emphasize that while current costs remain relatively high for most CO₂ conversion pathways, continued scale-up, process integration, and policy-driven carbon valuation can substantially improve the economic viability of CCU technologies in the near future.

While CCU technologies are primarily evaluated based on their ability to reduce net CO₂ emissions, it is equally important to consider their non-CO₂ environmental implications, which may offset some of the anticipated climate benefits if not properly managed. For instance, amine-based post-combustion capture systems can generate degradation products such as nitrosamines, nitramines, and formaldehydes, which pose potential risks to air and water quality. The formation and release of these compounds

depend on operating temperature, oxygen concentration, and solvent regeneration cycles, underscoring the need for careful process optimization and solvent management.

In catalytic CO₂ conversion pathways, particularly those involving nanostructured catalysts (e.g., CuO, TiO₂, or Ni-based nanocomposites), concerns have emerged regarding nanoparticle leaching, catalyst disposal, and potential ecotoxicity. These effects could arise from long-term exposure, catalyst attrition, or regeneration losses, necessitating the development of stable catalyst supports, encapsulation techniques, and circular recovery strategies.

Additionally, bioenergy-based CCU (BECCU) systems, while offering renewable carbon sources, may exert indirect land-use pressures, including competition with food crops and biodiversity loss if biomass feedstock demand increases substantially. Integrating sustainable biomass sourcing practices, carbon intensity certification, and waste biomass utilization can help mitigate these risks.

Therefore, a comprehensive life-cycle assessment (LCA) of CCU technologies should account for both CO₂ mitigation benefits and associated environmental trade-offs, ensuring that future deployments are aligned with broader sustainability and environmental safety objectives.

In a nutshell, CCC, CCU, CCUS, and ICCS techniques help in decreasing carbon footprints from the atmosphere, minimize the ill effects of global warming, improve the carbon economy, and produce useful chemical products. The CO₂ capture emphasizes diverse methodologies such as chemical absorption using solvents (mainly amine-based, caustic-based, Glycols, enzyme-based, etc.) adsorption by nanomaterials like AC, MOFs, and COFs, Cryogenic separation, ocean-based entrapment, DAC, ionic liquids, and membrane separation [33,161]. The production of useful chemical products like CH₄, CH₃OH, ethanol,

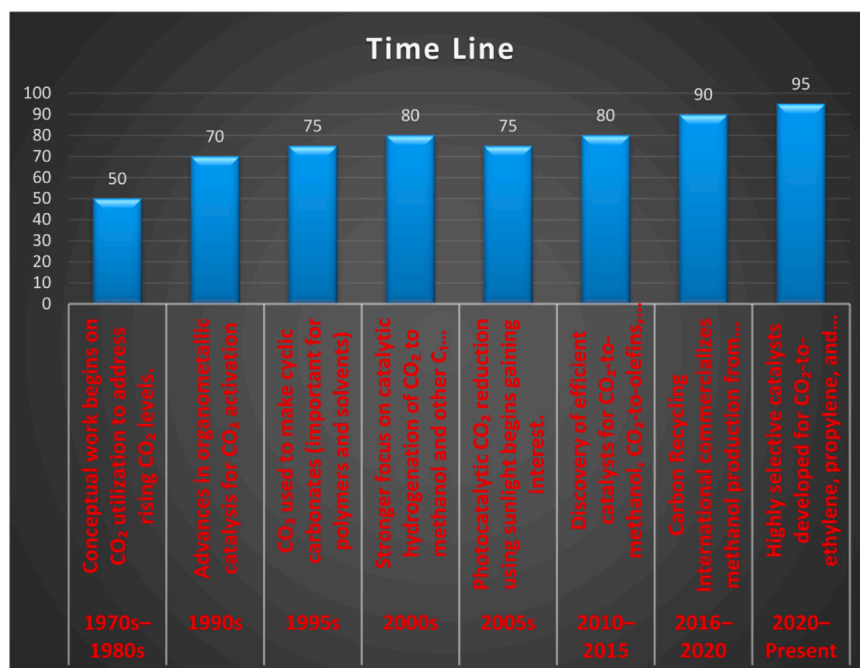


Fig. 10. Timeline of CO₂ capture and its conversion into useful products.

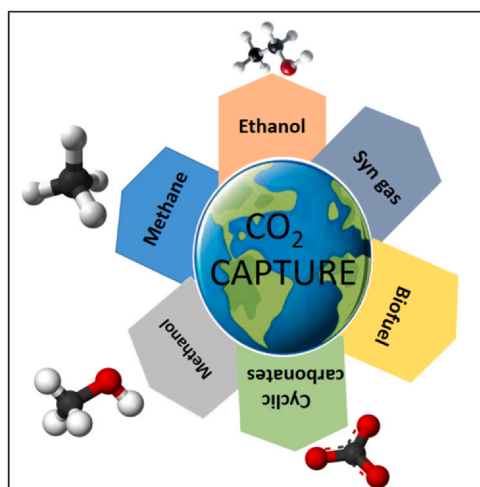


Fig. 11. CO₂ capture and its conversion to ethanol, Syn gas, Biofuel, Cyclic carbonates, methanol, and methane.

biofuel, Syngas, and Cyclic carbonates depends upon the efficiency of the CO₂ capture technique involved. CO₂ and H₂O can be electro-catalytically reduced to Syngas (CO and H₂). Syngas can be used for the synthesis of methanol, ammonia, hydrogen production, liquid fuels, hydrogen generation, hydroformylation reaction, acetylene production, bioenergy production, and metal reduction processes. By unraveling the intricate details of CO₂ conversion into valuable products—ethanol, biofuel, acetaldehyde, cyclic carbonates, methanol, and methane—it becomes evident that CCU and CCS technologies offer a multifaceted solution to the complex challenges of emissions reduction. A 100% methanol production efficiency was achieved using an Au/Zn/ZrO₂ catalyst in a co-precipitation method at a temperature of 220 °C. A maximum of 91% Faradaic ethanol conversion efficiency was achieved in electrocatalytic reduction of CO₂ using Cu/Carbon (0.4%) electrode in 0.1 M KHCO₃ electrolyte at an applied potential of -0.7 V and current -1.23 mA/cm². A maximum, i.e., 1200 mL/min of the CH₄ gas was produced by the CO₂ capture technique using DFM based on Ru/Na/Ca/Al₂O₃ material. CO₂ can be successfully converted into CC using

epoxides. CCs are essential intermediates in the synthesis of polycarbonates. Polycarbonates are high-performance plastics with applications in eyewear, electronics, and automotive components.

Electrocatalytic reduction of CO₂ to ethanol and biofuel in an alkaline medium shows a very good Faradaic conversion efficiency. Both single and bimetallic-based catalysts were proposed for electrocatalytic reduction of CO₂ to ethanol and other organic products [188,197]. Yagihara et al. reported recent CeO₂-based CO₂ capture and conversion to dual dual-function material. Advancement in CCC technologies and their industrial integration for sustainable development was reported. Recently, direct CO₂ capture for solar fuel production. The blending of petrol (fossil fuel) with ethanol (a maximum of 15%) creates a blended biofuel known as ethanol-blended petrol (EBP), which serves many purposes, primarily related to environmental and energy-related objectives.

9. Techno-economic and life cycle assessment perspectives of CO₂ utilization technologies

A comprehensive evaluation of CO₂ utilization pathways requires not only understanding their underlying Chemistry but also assessing their technological maturity, economic feasibility, energy efficiency, and environmental sustainability. While numerous conversion routes have demonstrated laboratory success, their large-scale deployment depends heavily on favorable techno-economic and life cycle performance indicators.

The current CO₂ utilization landscape exhibits wide variability in Technology Readiness Levels (TRLs) across different conversion routes. Mineral carbonation and urea synthesis are among the most mature processes, operating at TRL 8–9, with several commercial-scale demonstrations due to their thermodynamic simplicity and product stability. Catalytic hydrogenation of CO₂ to methanol and synthetic methane has reached TRL 6–8, with industrial pilots by companies such as Carbon Recycling International demonstrating feasibility. Conversely, electrochemical and photochemical reduction processes generally remain at TRL 3–5, limited by electrode stability, low current efficiency, and high energy demand. Biological fixation routes, using microalgae or engineered microorganisms, are also in early-to-intermediate stages (TRL 4–6), constrained by slow kinetics and process scalability.

Table 7
Comparative assessment of major CO₂ utilization technologies

Technology	Typical product	TRL	Energy efficiency (%)	Estimated cost (USD/Ton CO ₂ converted)	CO ₂ Reduction potential	Key limitations
CO ₂ → Methanol (Hydrogenation)	Methanol	6–8	60–70	600–1200	Moderate–High	High H ₂ cost, catalyst stability
CO ₂ → CH ₄ (Sabatier Process)	Synthetic Methane	6–8	70–80	400–900	Moderate	H ₂ supply, reactor optimization
CO ₂ → Carbonates (Mineralization)	Ca/Mg Carbonates	8–9	40–60	50–100	Very High	Low-value product, slow kinetics
Electrochemical CO ₂ Reduction	CO, Formate, Ethylene	3–5	30–50	> 1500	Moderate	High electricity input, low selectivity
Photocatalytic Conversion	CH ₄ , CH ₃ OH	3–4	10–20	> 2000	Low	Low quantum yield, scale-up challenge
Biological Fixation	Biomass, Biofuels	4–6	20–40	200–600	Moderate	Slow rate, large land/water demand

TRL = Technology Readiness Level.

Techno-economic assessments (TEAs) have revealed that the cost-competitiveness of CO₂ utilization depends predominantly on feedstock cost (especially renewable H₂), process energy intensity, and product market value. For instance, methanol production via CO₂ hydrogenation currently costs \$600–1200 per tonne, which is 1.5–3 times higher than conventional fossil-based methanol. However, cost parity can be achieved if renewable H₂ prices drop below \$2/kg and CO₂ capture costs below \$30/tonne. In contrast, mineral carbonation processes show lower costs (around \$50–100 per tonne CO₂ fixed) but yield low-value products. Electrochemical CO₂ reduction (ECR) offers flexibility and modularity but remains economically challenging, with electricity demand exceeding 5–8 MWh per tonne CO₂ converted and limited Faradaic efficiency for multi-carbon products. Integrating renewable power sources, improving catalyst selectivity, and developing coupled systems (e.g., photoelectrochemical or biohybrid) are key strategies for reducing overall cost and energy penalties.

The overall net carbon reduction benefit of CO₂ utilization technologies depends on whether the energy inputs originate from renewable sources. Hydrogenation and electrochemical routes can achieve up to 70–90% CO₂ conversion efficiency, but if powered by fossil-based electricity, the total carbon footprint can be neutral or even positive. Conversely, mineralization and biological routes inherently offer permanent CO₂ sequestration, though with slower kinetics. Life Cycle Assessment (LCA) studies indicate that the carbon payback time for synthetic fuels can exceed 12–15 years unless renewable energy integration exceeds 80% of the total energy input.

Recent LCA studies provide valuable metrics for identifying sustainable pathways. The production of methanol or formic acid via renewable-powered CO₂ hydrogenation can achieve 60–90% CO₂ reduction compared to fossil routes, while mineral carbonation can achieve nearly 100% sequestration efficiency. Electrochemical conversion of CO₂ to CO or ethylene shows promise but remains energy-intensive, with global warming potential (GWP) reductions of only 20–40% under current grid electricity conditions. Hybrid systems that integrate CO₂ capture, renewable H₂ production, and conversion in a single process train show the most promising LCA outcomes.

A horizontal comparison of major CO₂ utilization routes is summarized in Table 7, presenting their TRL, energy efficiency, cost range, and CO₂ mitigation potential. The analysis suggests that CH₃OH synthesis and mineralization are closest to large-scale deployment, whereas electrochemical and photochemical pathways represent long-term transformative technologies requiring breakthroughs in catalyst design, reactor engineering, and energy management. Future research should therefore prioritize coupled TEA–LCA frameworks, enabling dynamic assessments that integrate evolving renewable energy costs and carbon pricing mechanisms. This holistic perspective will be vital in steering both research and policy decisions toward technologies that offer the best trade-off between economic viability, scalability, and environmental benefit.

10. Conclusions

Carbon capture and utilization (CCU) technologies provide a sustainable approach to mitigating CO₂ emissions by converting captured

carbon into fuels and value-added chemicals, thereby promoting a circular carbon economy. This review highlights recent progress in CO₂ capture methods—absorption, adsorption using MOFs and ionic liquids, and membrane separation—and their integration with conversion pathways such as thermochemical hydrogenation, electrochemical reduction, and photocatalysis. Advances in catalyst systems, including Au/Zn/ZrO₂, Cu-based, and Ru/Na/Ca/Al₂O₃ materials, have enabled high conversion efficiencies toward methanol, ethanol, methane, and cyclic carbonates. Future efforts should emphasize catalyst durability, renewable energy coupling, and techno-economic optimization to enhance large-scale feasibility. While CCS may serve as a complementary strategy for permanent storage, the primary focus of this work is on CCU as a transformative route for CO₂ valorization—turning a greenhouse gas into a valuable industrial feedstock and contributing meaningfully to a net-zero carbon future. A 100% methanol production efficiency was achieved using an Au/Zn/ZrO₂ catalyst in a co-precipitation method at a temperature of 220 °C. A maximum Faradaic ethanol conversion efficiency of 91% was achieved in the electrocatalytic reduction of CO₂ using a Cu/Carbon (0.4%) electrode in a 0.1 M KHCO₃ electrolyte at an applied potential of −0.7 V and a current density of −1.23 mA/cm². A maximum of 1200 mL/min of CH₄ gas was produced using the CO₂ capture technique with DFM based on Ru/Na/Ca/Al₂O₃ material. CO₂ can be successfully converted into CC using epoxides. CCs are essential intermediates in the synthesis of polycarbonates. Polycarbonates are high-performance plastics with applications in eyewear, electronics, and automotive components. As we envision the future, it is clear that the trajectory of CCU and CCS technologies extends beyond mere emissions mitigation. It is a journey toward technological innovation, economic diversification, and the establishment of a circular Carbon economy.

In essence, this review article underscores the importance of current research and progress in the fields of CCU, CCUS, CCC, ICCS, and CCS. By unlocking the full potential of CCU technologies, we can not only reduce CO₂ emissions but also redefine our relationship with Carbon, transforming it from a threat into a valuable resource. As we stand at the intersection of innovation and environmental stewardship, the journey toward a sustainable tomorrow beckons. The path forward involves a commitment to collaboration, continuous improvement, and a shared vision of a world where CCU and CCS technologies play a central role in securing the health of our planet for generations to come.

11. Future perspectives

Future perspectives anticipate the integration of CCU, CCS, CCUS, ICCS, CCC, and IC³M strategies into global frameworks, with countries collaborating to set ambitious targets for CO₂ reduction through the widespread implementation of these transformative technologies. The ongoing demand for more efficient and sustainable CCU and CCS processes will drive technological innovations in catalyst design. Future research will likely focus on developing novel solvents, catalysts, and adsorbents that enhance selectivity, efficiency, and durability in CO₂ conversion. A shift from laboratory to industrial-scale applications is a critical step for the widespread adoption of CCU and CCS technologies.

Future perspectives envision concerted efforts to scale up existing CCU processes, addressing challenges related to cost-effectiveness, energy consumption, and integration with existing infrastructure. Successful scaling will position CCU and CCS as a mainstream solution for industrial Carbon emissions. Future research may uncover novel applications and markets for CCU-derived materials, expanding the range of valuable products that can be generated from captured CO₂. Certain sectors, such as heavy industries and aviation, present unique challenges for Carbon reduction. Future perspectives foresee increased efforts to implement CCU, CCUS, ICCS, and IC³M technologies in these hard-to-decarbonize sectors, paving the way for innovative solutions that contribute significantly to overall emissions mitigation. Collaboration between researchers, industry leaders, and policymakers will be crucial in overcoming technical and logistical challenges. Future perspectives suggest the development of comprehensive policy frameworks that promote research and development, incentivize industrial adoption, and facilitate international collaboration to address the multifaceted challenges associated with climate change. As CCUS and IC³M technologies become more prominent, public awareness and acceptance will play a pivotal role in their success. The evolution of CCU technologies from promising concepts to practical solutions hinges on continued interdisciplinary collaboration, innovation, and a collective commitment to addressing the challenges posed by climate change. By embracing the multifaceted future perspectives outlined above, one can collectively usher in an era where CCUS, ICCS, and IC³M technologies are central to the global strategy for achieving a sustainable and circular Carbon economy. To conclude, the future of CCU technologies holds immense promise.

12. Future research directions

The development of CO₂ conversion technologies toward commercially viable, sustainable products requires not only advances in catalytic chemistry but also integration across engineering, market, and policy domains. A critical assessment of the prevailing challenges for key value-added products is summarized below to guide future research focus.

The main limitations in methane production lie in thermodynamics and energy efficiency, as methanation is highly exothermic and requires precise temperature control to prevent catalyst sintering. Research over the next 5 years should emphasize catalyst stabilization, thermal management, and dynamic operation under fluctuating renewable energy inputs to enable grid-coupled synthetic natural gas production.

Methanol synthesis faces challenges in both catalyst activity–stability trade-offs (Cu–Zn, Pd–Zn, In₂O₃ systems) and process integration with renewable hydrogen. The priority should shift toward electrocatalytic and photo-assisted routes, enabling operation at lower pressures with minimal carbon intensity. Techno-economic optimization through renewable energy coupling and modular plant design is also crucial.

Ethanol and higher alcohols pathways remain largely limited by reaction selectivity and C–C coupling control, marking this as a fundamental chemistry challenge. Future research should target multifunctional catalysts, reaction mechanism elucidation, and *in situ* spectroscopic monitoring to improve selectivity toward ethanol over by-products such as methane or CO.

For the Cyclic Carbonates category, the chemistry is well understood, but the bottlenecks are largely engineering and market-driven. The mild thermodynamics of CO₂–epoxide coupling make the process feasible, yet feedstock availability, catalyst recyclability, and product market development limit deployment. The next research phase should focus on green solvent systems, biobased epoxide feedstocks, and scalable reactor designs.

Across all pathways, success will depend on cross-disciplinary collaboration—bridging catalysis, process engineering, life-cycle assessment, and policy mechanisms—to achieve true carbon circularity. Over the next 5 years, integrating policy incentives, carbon pricing mechanisms, and renewable energy deployment will be as critical as scientific innovation in ensuring the viability of CO₂ utilization technologies.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Harish Kumar reports administrative support and equipment, drugs, or supplies were provided by Central University of Haryana. Harish Kumar reports a relationship with Central University of Haryana that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors of this review article declare that we did not take the help of any AI tools in writing this review article.

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