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Complete List of Authors:	Wei, Kecheng; Brown University, Department of Chemistry Guan, Huanqin; Brown University Luo, Qiang; University of Connecticut He, Jie; University of Connecticut, Department of Chemistry Sun, Shouheng; Brown University, Chemistry

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REVIEW

Recent Advances in CO₂ Capture and Reduction

Kecheng Wei,^a Huanqin Guan,^a Qiang Luo,^b Jie He^{*b,c} and Shouheng Sun,^{*a}

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Given the continuous and excessive CO₂ emission into the atmosphere from anthropomorphic activities, there is now a growing demand for negative carbon emission technologies, which requires efficient capture and conversion of CO₂ to value-added chemicals. This review highlights recent advances in CO₂ capture and conversion chemistry and processes. It first summarizes various adsorbent materials that have been developed for CO₂ capture, including hydroxide-, amine-, and metal organic framework-based adsorbents. It then reviews recent efforts devoted to two types of CO₂ conversion reactions: thermochemical CO₂ hydrogenation and electrochemical CO₂ reduction. While the thermal hydrogenation reactions are often accomplished in the presence of H₂, electrochemical reactions are realized by direct use of electricity that can be renewably generated from solar and wind power. The key to the success of these reactions is to develop efficient catalysts and to rationally engineer the catalyst-electrolyte interfaces. The review further covers recent studies in integrating CO₂ capture and conversion processes so that energy efficiency for the overall CO₂ capture and conversion can be optimized. Lastly, the review briefs some new approaches and future directions of coupling direct air capture and CO₂ conversion technologies as solutions to negative carbon emission and energy sustainability.

1. Carbon Cycle and CO₂ Emission

Carbon is the chemical backbone of life on Earth. Carbon compounds regulate the earth's temperature, make up the food that sustains us, and provides the energy that drives the global economy. The carbon cycle in nature is the global flow of carbon through the atmosphere, oceans, terrestrial biosphere, and lithosphere in various forms, such as carbon dioxide, organisms, limestone, coal and oil, as shown in **Figure 1A**.¹ Two main cycles are the land-atmosphere cycle and the ocean-atmosphere cycle.^{2, 3} The land-atmosphere cycle occurs through two main drivers: photosynthesis and respiration. In the photosynthesis process, CO₂ is absorbed from the atmosphere and converted into fuels by plants or microbes, while in the respiration process CO₂ is produced as the final product from biological activities. In comparison to the land-atmosphere cycle, the ocean-atmosphere cycle plays a vital role in carbon storage because it contains 50 times more carbon than the atmosphere.^{4, 5} The driving mechanism of the ocean-atmosphere cycle is the difference in the partial pressure of CO₂ between the ocean and the atmosphere. This pressure varies with ocean temperature and local marine photosynthesis. The lower the ocean temperature, the less the carbon emissions.⁶ In all, nature balances these cycles well in equilibrium, maintaining the healthy evolution of life. Over the past century, however, fossil fuels have been massively consumed for energy uses (**Figure 1B**).^{7, 8} This has resulted in a dramatic increase in atmospheric

CO₂, and as a result, caused a series of environmental issues, including global warming, acid rain, ocean acidification and rising of sea levels (**Figure 1C**).⁷⁻¹⁰

2. CO₂ Capture

To combat anthropogenic CO₂ emission and to make our lifestyles sustainable, we must develop neutral or even negative carbon emission technologies. One of such technologies is CO₂ capture and storage.^{11, 12} Recent studies have shown that the key barrier that limits the broad uses of this process is high energy penalty associated with the CO₂ capture,¹² which is aggravated by the fact that about half of annual CO₂ emission is generated from widespread industry sites. In 1999, Lackner introduced the concept of direct air capture of CO₂ to mitigate climate change and it is now broadly defined as direct extraction of CO₂ from ambient air.¹³⁻¹⁶

A key step to successful CO₂ capture is to develop efficient adsorbents to bind CO₂ from air. An ideal CO₂ adsorbent should have high selectivity and adsorption capacity for CO₂, low heat of adsorption (Q_{st}), high recyclability, good thermal and chemical stability, fast kinetics and high cost-effectiveness (**Figure 2**).¹⁷ The energetics of the CO₂ capture process is about the chemical bonding nature between CO₂ and an adsorbent, which can involve both weak physisorption and strong chemisorption. Such binding strength is defined by isosteric heat of adsorption Q_{st} (kJ/mol). For a given adsorbent, a high Q_{st} value indicates an energy-intensive CO₂ regeneration process once it is captured, whereas a low Q_{st} value may compromise

^a Department of Chemistry, Brown University, Providence, Rhode Island 02912, USA

^b Department of Chemistry, and ^c Polymer Program, Institute of Materials Science, University of Connecticut, Storrs, Connecticut 06269, USA

E-mail: jie.he@uconn.edu, ssun@brown.edu

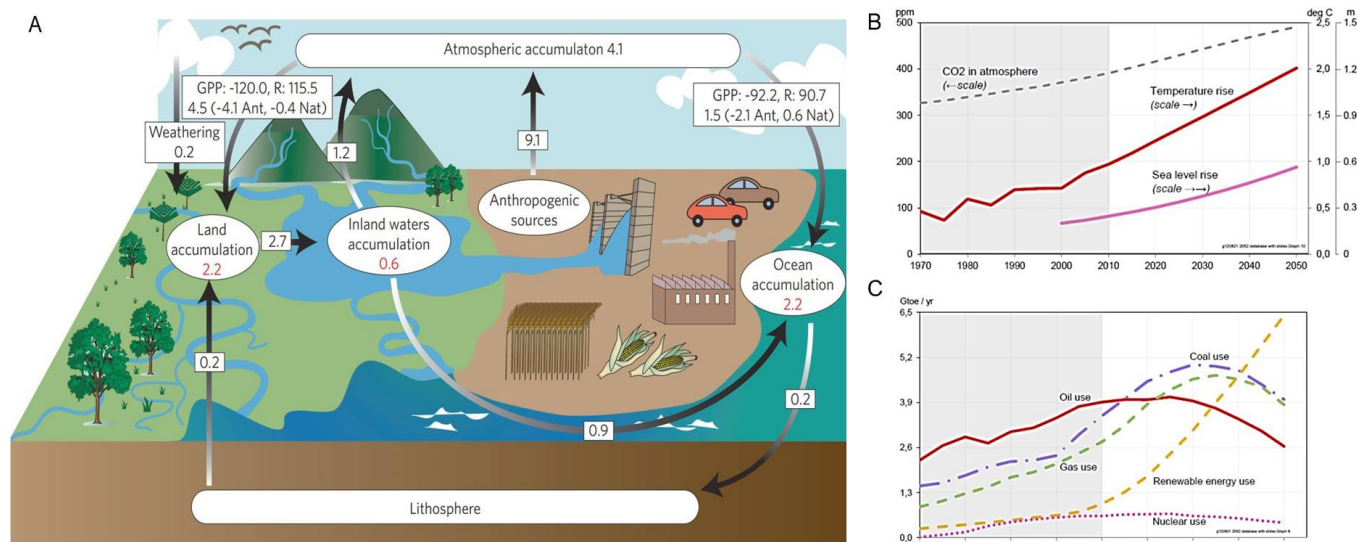


Figure 1. (A) The schematic highlights carbon fluxes through inland waters and includes pre-industrial and anthropogenic fluxes. Values are net fluxes between pools (black) or rates of change within pools (red); units are Pg C yr^{-1} ; negative signs indicate a sink to the atmosphere. Gross fluxes from the atmosphere to land and oceans, and the natural (Nat) and anthropogenic (Ant) components of net primary production — the net uptake of carbon by photosynthetic organisms — are shown for land and oceans. Gross primary production (GPP) and ecosystem respiration (R). (B) Energy source in the past and forecast from 1970 to 2050, and (C) CO_2 concentration in atmosphere, global temperature, sea level. Adapted from ref. 1, 9 with permission. Copyright 2009 Nature Publishing Group and 2012 Chelsea Green Publishing.

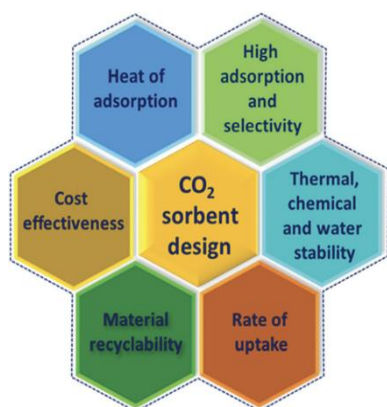


Figure 2. Principal criteria for designing an ideal sorbent for CO_2 capture. Reprinted from ref. 17 with permission. Copyright 2020 Royal Society of Chemistry.

the CO_2 adsorption capacity. Furthermore, a good adsorbent should have high selectivity adsorbing CO_2 from a mixture of gases, especially from air, and have high thermal, chemical, and water stability to achieve high CO_2 capture efficiency in different operation conditions. The rate of CO_2 uptake should also be kinetically fast, the capture process be easily engineered to large scale, and the overall cost for the capture process be economically practical. Here we summarize some representative adsorbents that have been studied extensively for the CO_2 capture, including aqueous hydroxide, solid alkali carbonates, organic amines, and porous materials.^{18, 19}

2.1. Hydroxide-Based Adsorbents

Due to the relatively low concentration of CO_2 (412 ppm) in the atmosphere, CO_2 capture is usually carried out using chemical adsorbents with a strong CO_2 binding affinity. A common adsorbent is calcium hydroxide solution, which can

react with CO_2 and form calcium carbonate as precipitate. Then calcium carbonate can be separated and dried for storage. The captured CO_2 can be accessed through a process known as calcination — the decomposition of calcium carbonate to form calcium oxide with CO_2 being released as a concentrated stream. Calcium hydroxide is then regenerated in a slaking process via hydration of calcium oxide, forming a recyclable loop.¹⁴ Many different types of adsorption devices, from traditional stagnant pools, packed towers, to modern spray towers, have been designed and developed.²⁰ Alternatively, solid inorganic bases are used for ultra-dilute CO_2 removal. **Figure 3** plots the equilibrium partial pressure of CO_2 , $p_{\text{CO}_2, \text{eq}}$, as a function of temperature (T), for various single-metal oxide

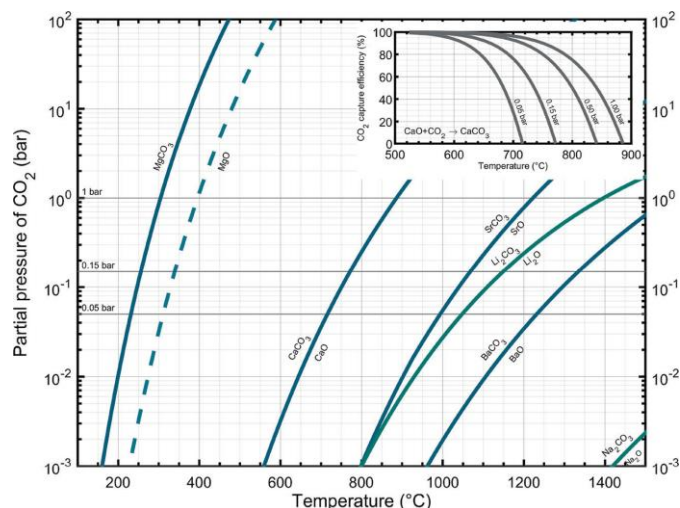


Figure 3. Equilibrium partial pressure of CO_2 , $p_{\text{CO}_2, \text{eq}}$, as a function of temperature for alkali (green) and alkaline earth (blue) metal oxide-carbonate systems. Horizontal gray lines indicate p_{CO_2} of 0.05, 0.15, and 1 bar, respectively. Reprinted from ref. 21 with permission. Copyright 2008, 2021 American Chemical Society.

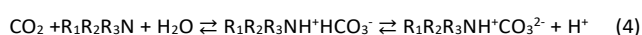
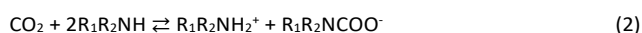
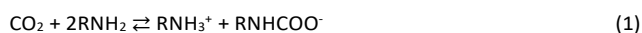
sorbents. Combinations of T and p_{CO_2} above the respective $p_{\text{CO}_2, \text{eq}}$ curves imply the material exists as carbonate, whereas below the curve, the material's thermodynamically stable state is its oxide form.²¹ The thermodynamic properties of the CaO–CaCO₃ system enables the direct capture of CO₂ from ambient air ($p_{\text{CO}_2} = 4 \times 10^{-4}$ bar). To release CO₂ from CaCO₃, high temperatures (> 900 °C) are generally required to obtain a pure stream of CO₂ ($p_{\text{CO}_2} \approx 1$ bar). Despite the convenient chemistry involved in the process, dealing with a large volume of air, hydroxide solution, and metal carbonate decomposition can impose heavy energy cost due to the high temperature required to regenerate the metal oxide adsorbents and to release CO₂.

2.2. Amine-Based Adsorbents

Amines are another common adsorbent employed for CO₂ capture. Using aqueous solution of amines to capture CO₂ has been extended to commercial uses to remove CO₂ from CO₂-rich natural gas streams.²² To date, amine adsorbents employed for direct air capture are supported on solids to improve amine stability and recyclability. The strength of chemisorption between an amine and CO₂ ensures selective CO₂ uptake even at low CO₂ partial pressures, which makes the solid-supported amine adsorbents highly suitable for the direct air capture of CO₂.

In a dry condition, CO₂ reacts with either a primary amine (equation 1) or secondary amine (equation 2) to produce an ammonium carbamate. When moisture is present, the reaction yields ammonium carbonate or bicarbonate (depending on the pH) (equation 3 and 4).¹⁴ Amine-containing sorbents have been divided into three classes: class 1 amine adsorbents are prepared by impregnating amines into the pores of a support;

class 2 amine adsorbents are formed by covalently bonding amines to the walls of porous materials via silane linkage; and class 3 amine adsorbents are derived from polymerization of amines in situ to form polyamine structures tethered to the inner walls of the porous support.^{14, 23–25} **Figure 4** shows some representative examples of these amine adsorbents. After adsorption, CO₂ can be released from the adsorbent by an inert gas flow to drive the reaction equilibrium towards gaseous CO₂.^{14, 26} An advantage of the amine adsorbent over the metal oxide one is its selective adsorption of CO₂ over H₂O, making it useful in the humid environment.²⁷



2.3. Adsorbents Based on Metal Organic Frameworks (MOF)

Due to the difficulty in cleaving the adsorbent–CO₂ bond in carbonate or carbamate, which requires a large energy input to regenerate adsorbents, weak physisorption of CO₂ by porous materials has been explored extensively as an alternative to chemisorption to improve energy efficiency of the capture process. Significant research progress has been made in CO₂ capture by micro and mesoporous materials, including metal–organic frameworks (MOF), zeolites, zeolitic imidazole frameworks (ZIF), and porous polymers.^{13, 17, 28, 29} MOFs consist of three-dimensional coordination polymer networks, constructed by the combination of metal ions/clusters with organic linkers/ligands. **Figure 5** shows crystalline structures of some well-known MOFs.³⁰ Their CO₂ adsorption power can be

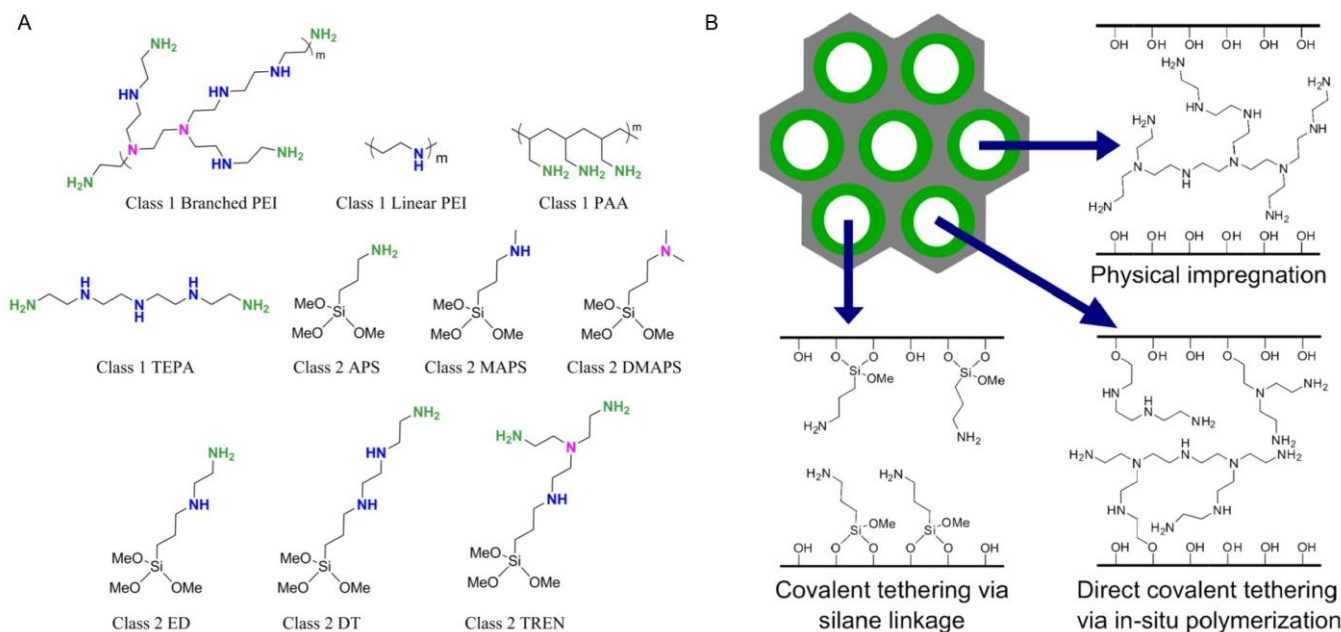


Figure 4. (A) Molecular structures of commonly used amines for class 1 and class 2 direct air capture sorbents. (B) Schematic representation of the three main routes used for functionalization of porous supports with amine moieties. Reprinted from ref. 14, 26 with permission. Copyright 2016 American Chemical Society and 2016 Georgia Institute of Technology.

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tuned more conveniently by specific surface areas, pore-volumes, pore sizes, metal centres, and surface functional groups, which make them especially attractive for selective CO₂ capture from a stream of gas mixture.

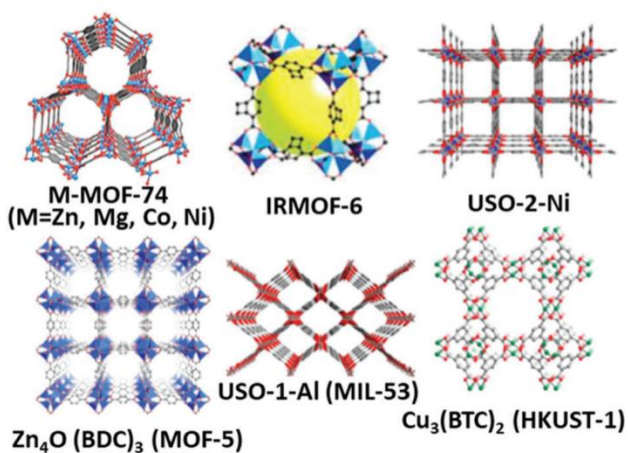


Figure 5. The crystalline structure of some well-known MOFs. Reprinted from ref. 30 with permission. Copyright 2019 Elsevier.

2.3.1. CO₂ Adsorption via Metal-Binding in MOFs

As the pore structures of MOFs are sensitive to the adsorption of CO₂, functionalization of the inner and outer surface the MOFs can tune their adsorption power. A typical approach is to make MOFs with unsaturated open metal sites (UOMSs), which can be prepared by heating or vacuuming of the solvent coordinated metal cations in MOFs.^{30, 31} These exposed metal-coordination sites can build an electric field around them, providing the desired driving force for CO₂ adsorption. M-CO₂ binding is realized by direct interaction between the antibonding dz² orbital and the lone electron pairs on the oxygen in the CO₂ molecule. For an early transition metal cation with d electrons less than 4, its antibonding d-orbitals tend to bind to CO₂ more strongly. But for a late transition metal cation, its antibonding orbitals can be filled up, weakening its binding with CO₂.³² For example, Mg₂(dobdc) (H₄dobdc = 2,5-dihydroxyterephthalic acid), Mg-MOF-74, and CPO-27-Mg structures with open metal sites bound to CO₂ at a fixed angle in a uniaxial fashion, as shown in **Figure 6A**.³³ Their CO₂ binding energies are around 67.2 kJ/mol (**Figure 6B**).³⁴ In the presence of the early transition metal (Ti or V) cation, their binding energies are improved to 73.2–80.2 kJ/mol, while in the presence of the late transition metal (Cr or Zn) cation, their binding energies are dropped to 32.2–50.8 kJ/mol (**Figure 6B**).

2.3.2. Enhancing CO₂ Adsorption via Functionalization of MOFs

MOFs modified with functional groups can change their surface properties and CO₂ adsorption power. A common strategy to modify MOFs is to add polar or amine-based moieties to the structure to enhance their interactions with CO₂, especially at low-pressure conditions. However, this enhancement needs to be regulated more carefully as the strong interaction with CO₂ also makes it difficult to regenerate

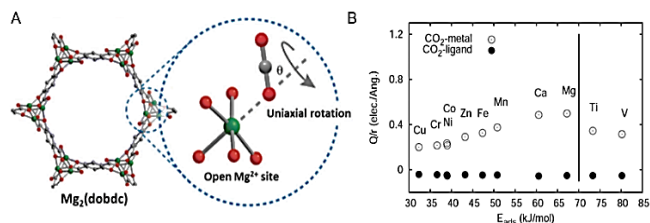


Figure 6. (A) Schematic illustration of CO₂ uniaxial rotation at the open Mg²⁺ site in Mg₂(dobdc). Gray – C, red – O, and green – Mg atoms; H atoms are omitted for clarity. The blue circle is the arbitrary rotation axis. (B) CO₂ adsorption energy plotted over Q/R computed for the metal–CO₂ oxygen distance and the tetrazole nitrogen–CO₂ carbon distance. The vertical line is to guide the eye. Reprinted from ref. 33, 34 with permission. Copyright 2012 and 2014 American Chemical Society.

the MOF adsorbent. Therefore, this functionalization should enable MOFs to show high CO₂ adsorption affinity, capacity, selectivity, but low Q_{st}.

As an example, isorecticular MOF (IRMOFs)-74-III was functionalized with a series of organic linkers –CH₃, –NH₂, –CH₂NHBoc (Boc: tert-butyloxycarbonyl), –CH₂NMeBoc, –CH₂NH₂, and –CH₂NHMe via the Suzuki–Miyaura coupling reaction (**Figure 7A**).^{35, 36} All the modified MOFs, except the ones containing the protective Boc groups, showed high and similar CO₂ adsorption behaviours at 25 °C/800 Torr, as shown in **Figure 7B**.³⁶ However, at low pressure, primary amine- and secondary amine-functionalized MOFs (IRMOF-74-III-CH₂NH₂ and IRMOF-74-III-CH₂NHMe, respectively) outperformed the other modified MOFs (**Figure 7C**).³⁶ A second CO₂ isotherm after evacuation of the sample at room temperature for 2 h and a third cycle with a heat treatment at 120 °C under vacuum (10 mTorr) for 1 h were recorded (**Figure 7D,E**).³⁶ The decrease in CO₂ uptake on the second cycle and recovery upon heat treatment indicated a strongly bound CO₂. Further exploration of IRMOF-74-III-CH₂NH₂ using dynamic CO₂ adsorption under dry (16% CO₂; 84% dry N₂) and wet (16% CO₂; 84% wet N₂) experimental conditions showed a negligible difference in the uptake rates for the CO₂ adsorption, suggesting the unique structural selectivity towards CO₂. ¹³C NMR studies showed that the capture was realized by chemisorption between CO₂ and the functionalized organic linkers, forming carbamate ions and carbamic acids for IRMOF-74-III-CH₂NH₂ and IRMOF-74-III-CH₂NHMe, respectively. Incorporation of diamine groups into the same MOF to form IRMOF-74-III-(CH₂NH₂)₂ could provide an even higher CO₂ adsorption power at 25 °C/800 Torr (75 cm³ g⁻¹) than that of IRMOF-74-III-CH₂NH₂ (67 cm³ g⁻¹).³⁷

2.3.3. MOF Pore Size-Dependent CO₂ Adsorption

The pore size is a third common parameter that can be applied to control MOF's CO₂ adsorption capability and selectivity. It is possible to synthesize MOFs with microporosity, mesopores or macropores which can be controlled by the nature of the starting metal precursor and the organic linkers used during the synthesis.^{38, 39} For example, MOFs with pore size of 2.6, 2.4, and 2.2 nm could be synthesized using cobalt-organic linkers with slightly different configurations (IR-MOF-74-III).⁴⁰ The benzene rings were termed as pore size tuners and

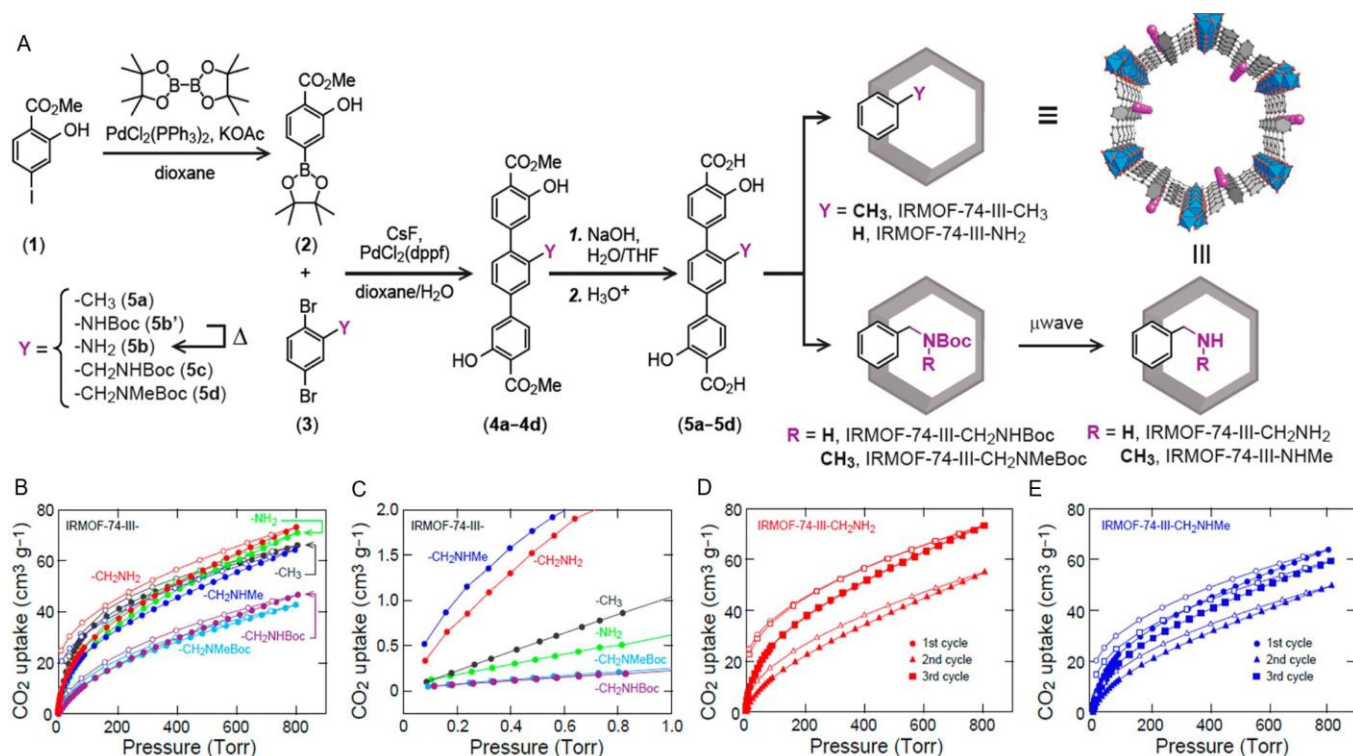


Figure 7. (A) Synthetic pathway for the functionalized organic linkers used in the synthesis of IRMOF-74-III, in the preparation of $-\text{CH}_3$ (5a), $-\text{NH}_2$ (5b), $-\text{CH}_2\text{NHBOc}$ (5c), and $-\text{CH}_2\text{NMeBOc}$ (5d) functionalized linkers. On the right is shown a schematic representation of the IRMOF-74-III pore as functionalized with the organic linkers 5a–5d and post-synthetic deprotection of Boc groups. Color code: C in gray, O in red, functional groups in purple, Mg as blue polyhedra. (B) Comparison of CO₂ uptake at 25 °C for IRMOF-74-III-CH₃ (gray), $-\text{NH}_2$ (green), CH_2NH_2 (red), $-\text{CH}_2\text{NHMe}$ (blue), $-\text{CH}_2\text{NHBOc}$ (purple), and $-\text{CH}_2\text{NMeBOc}$ (cyan). (C) Expansion of the low-pressure range (>1 Torr). Carbon dioxide isotherms at 25 °C for IRMOF-74-III-CH₂NH₂ (D) and $-\text{CH}_2\text{NHMe}$ (E). Uptakes for samples after activation (first cycle), after first CO₂ uptake (second cycle), and after 120 °C heating for 1 h for regeneration (third cycle) are shown in circles, triangles, and squares, respectively. Reprinted from ref. 36 with permission. Copyright 2014 American Chemical Society.

the CO₂ adsorption of the three MOFs was enhanced as the pore size decreased from 2.6 to 2.2 nm. The competing adsorption of water could be suppressed by narrowing down the pore size as suggested by computational calculations and experimental demonstration on MOF-74 by inserting 2,4,6-tri(4-pyridyl)-1,3,5-triazine (tpt) into its hexagonal channels.⁴¹

3. CO₂ Reduction

Despite the fact that CO₂ capture is important to solve CO₂ emission problems, to realize energy sustainability, CO₂ must be converted back into chemical fuels, which requires the controlled reduction and protonation of CO₂. This process is unfortunately an energetically uphill battle due to the high activation energy needed to break the stable O=C=O bond and the apparent difference in free energy between CO₂ and the final products. For this reaction to be economically viable, suitable catalysts with high catalytic activity, selectivity and stability must first be developed to achieve energy efficient reduction of CO₂. Many chemistry processes, including thermochemistry, electrochemistry, photochemistry, and biochemistry processes, have been studied for CO₂ reduction. In this section we highlight the recent advances in thermo- and electro-catalytic reduction of CO₂.

3.1. CO₂ Activation

CO₂ is a very stable molecule, with a bond dissociation energy of 525.9 kJ mol⁻¹ and ionization potential of 13.777 eV, making CO₂ activation difficult and costly.⁴² One-electron reduction of CO₂ is believed to be the first step to initiate the reduction and other reaction processes that convert CO₂ to reusable forms of carbon. The electronic structure of CO₂ in different charge states can be summarized in its Walsh diagram (Figure 8A).⁴³ In the ground state of neutral CO₂, the highest occupied molecular orbital (HOMO) is the fully occupied $1\pi_g$ orbital. An excess electron will be accommodated in the $2\pi_u$ orbital, which is stabilized by bending the molecule, leading to a deviation of the molecular symmetry from $D_{\infty h}$ to C_{2v} . The singly occupied molecular orbital (SOMO) in this radical anion is of a_1 symmetry, with an OCO angle calculated to be 138°, and it can be described as pseudo-antibonding. At the same time, the bonding $1\pi_g$ orbital transforms into a_2 and b_2 orbitals that have been characterized as largely nonbonding.⁴⁴ Consistent with the pseudo antibonding nature of the HOMO of CO₂⁻, its C–O bond length (124 pm) is greater than that of the neutral CO₂ (117 pm).

The free CO₂⁻ radical anion is metastable and has been observed in mass spectrometry with measured lifetime up to milliseconds.⁴⁴ The radical anion can be stabilized by interaction with a matrix or by solvation. The solvated CO₂⁻ radical anion has been observed in bulk solutions as well as in (CO₂)_n⁻ (n = 6–13) cluster ions.⁴⁴ While the first electronic excited state of neutral CO₂ is in the deep ultraviolet (UV), the radical anion has its lowest excited state in the near UV range. The electronic

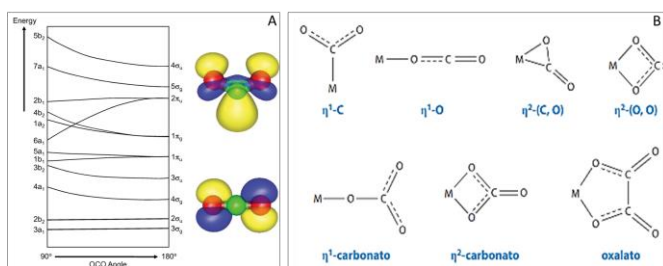


Figure 8. (A) Walsh diagram of CO_2 , with illustrations of the highest occupied molecular orbitals of the anion (top) and the neutral (bottom). (B) Structural motifs of metal- CO_2 interactions. Reprinted from ref. 43, 44 with permission. Copyright 2014 Abingdon: Taylor & Francis, and 2018 Annual Reviews.

absorption band of CO_2^- is at about 235 nm and CO_2^- can dissociate upon excitation and lose its excess electron by charge transfer, making it challenging to fully characterize CO_2^- .

Understanding the binding between CO_2 and a metal surface is of great importance for developing a metal catalyst to catalyse CO_2 reduction reaction. CO_2 can bind to metal atoms via different binding motifs, as summarized in **Figure 8B**.⁴⁴ These modes are abbreviated as $\eta^1\text{-C}$, $\eta^1\text{-O}$, $\eta^2\text{-(C,O)}$, and $\eta^2\text{-(O,O)}$, where superscripts denote the number of bonds between the metal atoms and bound CO_2 , and the chemical element symbols describe the atoms directly interacting with the metal. Electron reduction of metal- CO_2 leads to the formation metal- CO_2 cluster anions, $[\text{M}(\text{CO}_2)_n]^-$ that can serve as simplified models for studying CO_2 binding to metal atoms present on catalyst surfaces.⁴⁵⁻⁴⁷

3.2. Thermal Reduction of CO_2

The reduction of CO_2 in a thermo-catalytic process has attracted much attention as it not only reduces CO_2 emission, but also directly produces value-added chemicals and fuels.⁴⁸ To transform CO_2 to downstream products, its thermodynamic reaction barrier must be overcome.⁴⁹ Using H_2 as a high energy reactant to reduce CO_2 has been a common approach as H_2 can be generated from water electrolysis by renewable (solar or wind) electricity.⁴⁸ Therefore, this conversion of CO_2 by catalytic thermo-hydrogenation is one of the most attractive approaches to sustainable energy and carbon-neutral cycle (**Figure 9A**).⁵⁰

3.2.1. Reversible Water Gas Shift (RWGS) Reaction to CO

CO is considered as the most crucial intermediate in CO_2 conversion as it can be used in methanol synthesis and Fischer-Tropsch (FT) synthesis of various chemicals and fuels (**Figure 9B**).⁵¹ CO is generally produced by the reversible water gas shift (RWGS) reaction, in which CO_2 is hydrogenated under a high temperature and high pressure condition. However, this reaction quickly reaches its equilibrium, and as a result, the reaction has a low conversion yield (23%) at 300 °C and 1 MPa.⁵² Two mechanisms have been reported to explain the CO_2 hydrogenation to CO. The first one is a redox mechanism, which is usually observed on the surface of Cu-based catalysts. CO_2 is reduced by Cu^0 to form CO^* , which is desorbed from the surface to form CO product, and Cu^+ is then reduced back to Cu^0 by H_2 with water being formed as a byproduct.⁵³ This is further

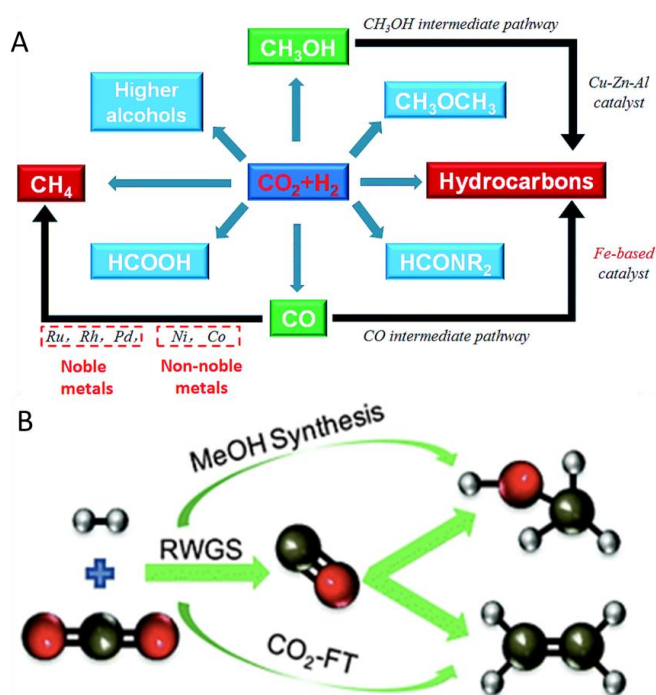


Figure 9. (A) Conversion of CO_2 to chemicals and fuels through hydrogenation. (B) Schematic illustration of cycles between RWGS, CO_2 -FT and Methanol synthesis. Reprinted from ref. 50, 51 with permission. Copyright 2016, 2018 Royal Society of Chemistry.

supported by density functional theory (DFT) calculations and Fourier-transform infrared spectroscopy (FTIR) spectroscopy studies over a Cu/ZnO catalyst.⁵⁴ The CO_2 hydrogenation may also follow the formate pathway, in which CO_2 is first converted to formate that is further dehydrated to form CO.⁵⁵

Metals on the oxide supports are considered as promising catalysts as the metal centres could easily dissociate H_2 , which is followed by transfer of H^* to CO_2 adsorbed on the oxide support.⁵⁶ Various catalysts based on transition metals on different oxide supports have been studied for the RWGS reaction. Among them, Cu or Pt-based catalysts supported on CeO_2 are the most extensively studied.⁵⁷ In studying monometallic and bimetallic Pt based catalysts on different oxide supports for selective CO_2 conversion to CO, it was found that active metal controlled the product selectivity, while the support effect dominated the activity of CO_2 conversion.⁵⁸ For the monometallic Pt catalysts, a reducible support (CeO_2) showed higher activity than on an irreducible support ($\gamma\text{-Al}_2\text{O}_3$) because of the increased oxygen vacancies found in the CeO_2 structure that is beneficial for oxygen exchange with CO_2 . Among the bimetallic Pt based catalysts supported on CeO_2 , PtCo showed the highest CO selectivity with little CH_4 production due to the weak binding of CO on the metal surface (**Figure 10A**).⁵⁸ Based on the d band theory, the CO/ CH_4 ratio selectivity increases when the values of d-band centre move towards more negative values for the Pt, Co, and Ni based catalysts on either CeO_2 or $\gamma\text{-Al}_2\text{O}_3$ supports (**Figure 10B**).⁵⁸ Such correlation between CO selectivity and metal d-band centre is

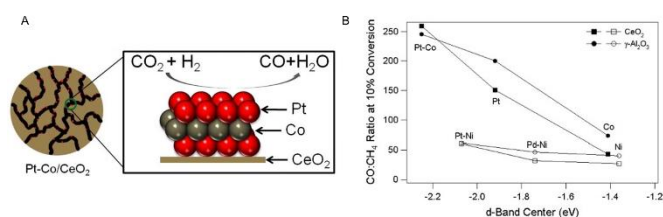


Figure 10. (A) Pt-Co/CeO₂ for CO₂ hydrogenation to CO. (B) Effect of d-band centre on ratio of CO to CH₄ production at 10% conversion. For ease of comparison, open and solid symbols represent catalysts with and without Ni, respectively. Reprinted from ref. 58 with permission. Copyright 2013 Elsevier.

potentially helpful for predicting selective CO₂ reduction catalysts.

In addition to Pt, other precious metals, such as Ir, Ru, Rh and Pd, are reported to be highly active hydrogenation catalysts.⁵⁹ Alternatively, Cu, Fe and Ni-based catalysts are also explored for large scale RWGS.⁶⁰ Cu/CeO₂ was found to be especially active as a RWGS catalyst at low temperature (300 °C) and ambient pressure, reaching 100% CO selectivity.⁶¹ The enhanced activity was attributed to synergies of Cu nanoparticle (NP) and CeO_x support in their redox behaviours and oxygen vacancies (Figure 11A).⁶¹ In-situ Ce L₃-edge XANES measurement for CeO₂ and Cu-CeO₂ supported on mesoporous silica SBA-15 (denoted as S Ce and SCuCe respectively) were performed during sample reduction at 300 °C in H₂ (Figure 11B, C).⁶¹ No change was observed in S Ce after reduction, while there is partial reduction of Ce⁴⁺ to Ce³⁺ for SCuCe. Similarly, Cu structure change upon CO₂ treatment at 120 °C was detected

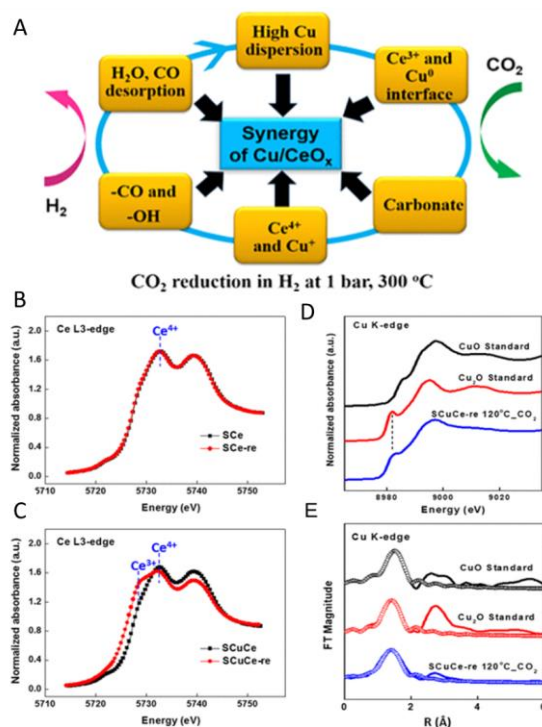


Figure 11. (A) Schematic illustration of synergy of Cu/CeO_x for CO₂ hydrogenation. (B-E) XAS spectra of Cu and Ce oxidation state change during reaction (note that S Ce = SBA-supported CeO₂ and SCuCe = SBA-supported Cu-CeO₂). Adapted from ref. 61 with permission. Copyright 2018 American Chemical Society.

by in situ X-ray absorption spectroscopy (XAS) measurement (Figure 11D, E).⁶¹ The spectra corresponded well with the Cu₂O standard, suggesting that Cu⁰ species in SCuCe-re are oxidized to Cu⁺ species via CO₂ treatment at 120 °C.⁶¹ The rapid desorption of CO from Cu⁺-CO intermediate at the reaction temperature led to product formation, which is followed by facile reduction of Cu and Ce by hydrogen spillover. The results suggest that the synergistic effect between oxygen vacancies and Cu redox property is essential for the oxide supported Cu catalyst to show high RWGS activity and selectivity.

3.2.2. Thermal Reduction of CO₂ to Methanol

Methanol is an important chemical feedstock for uses in combustion engines, fuel cells, and in the synthesis of downstream value-added products, such as dimethyl ether and hydrocarbons.⁶² The so called "methanol economy" is an indispensable and promising component in the carbon capture and conversion process to achieve carbon neutral cycle.⁶³ In fact, 140 million tons of methanol were produced in 2018 and its production is expected to double by 2030.⁶⁴ Conventionally, methanol is produced from syngas (CO + H₂) over a Cu/ZnO/Al₂O₃ catalyst at 200-300 °C and 3.0-5.0 MPa, but further studies indicate that CO₂-blended syngas shows higher reaction rates than syngas alone under the same reaction conditions.^{62, 65} As a result, direct hydrogenation of CO₂ to methanol has been a hot trend of research. Oxide-supported Cu catalysts are popular choices for methanol synthesis from CO₂. In the Cu/ZnO catalyst system, the high catalytic activity is attributed to the special Cu/ZnO interfacial and CuZn surface alloy effects, as confirmed by studying CuZn(111) and ZnO/Cu(111) catalysis.⁶⁶ In this study, CuZn was found to undergo surface oxidation under reaction conditions and the surface Zn was transformed into ZnO. The catalysis showed a volcano-plot trend between methanol production and ZnO coverage on Cu(111) (Figure 12A, B).⁶⁶ Similarly, CuZn(211) catalysis was further enhanced once the CuZn surface was partially covered with ZnO. The catalysis enhancement was attributed to the strong metal-support interaction, which strengthens the surface binding to intermediates and increases the catalytic activity.⁶⁷

Since CO₂ conversion to methanol is sensitive to catalyst structure, it is important to maintain the catalyst dispersion and prevent the catalyst from sintering and deactivation under the reaction conditions.⁶⁸ Various strategies have been proposed to

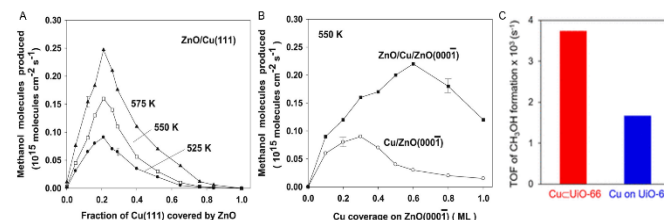


Figure 12. (A, B) CO₂ conversion to methanol. (C) Initial TOFs of methanol formation over Cu@UiO-66 and Cu on UiO-66. The reaction rates were measured after 1 h. Reaction conditions: 7 sccm of CO₂, 21 sccm of H₂, 10 bar, and 175 °C. Adapted from ref. 66, 70 with permission. Copyright 2017 American Association for the Advancement of Science and 2016 American Chemical Society.

solve the deactivation issues, including the use of reducible supports and encapsulation of Cu in metal organic frameworks (MOFs).^{69, 70} For example, Cu-MOF based composite catalyst was prepared by encapsulating Cu within the Zr-based UiO-66 porous structure.⁷⁰ The stabilized Cu showed much higher activity toward methanol formation (Figure 12C).⁷⁰ Additionally, the SiO₂-supported Ni-Ga intermetallic catalyst was found to be more active than the conventional Cu/ZnO/Al₂O₃ catalyst for the CO₂ reduction to methanol at ambient pressure.^{71, 72} A specific stoichiometric ratio (Ni₅Ga₃) was required in the catalyst formulation, which was stabilized by SiO₂, to achieve high selectivity. Interestingly, redox active In₂O₃ was also found to be a promising catalyst component with high methanol selectivity and remarkable stability due to its ability to form oxygen vacancies and metallic In in the reaction process.⁷³ Once the In₂O₃ catalyst was supported on ZrO₂, its catalytic activity was further improved and the methanol selectivity reached 99.8% with a CO₂ conversion of 5.2% and long-term stability of 1000 h under the industrially relevant reaction conditions.

3.2.3. Fischer-Tropsch Reaction

The C₂₊ hydrocarbons, such as alkanes, olefins and liquid fuels, are important for today's chemical and energy industries. For example, olefins are currently produced on the order of 200 Mt per year and widely used in synthetic rubbers, plastics and cosmetics.⁷⁴ However these hydrocarbons are traditionally generated from non-renewable fossil fuels, which results in large amounts of CO₂ emission.⁷⁵ Ideally, CO₂ can be used as a precursor for the synthesis of these hydrocarbons.⁷⁶

Fischer-Tropsch (FT) reaction is a common route for the transformation of syngas (CO + H₂) to C₂₊ hydrocarbons. To achieve the direct hydrogenation of CO₂, two successive reaction steps need to be incorporated in one reaction system, the reduction of CO₂ to CO via RWGS reaction and hydrogenation of CO to hydrocarbons via FT reaction.⁷⁷ In the two-step reaction process, the CO conversion (up to 87%) is much higher than the CO₂ conversion (up to 45%). Therefore, improving catalytic efficiency of the CO₂ conversion has been an important target.⁷⁷⁻⁸⁰ Fe-based catalysts have been widely used in CO₂ hydrogenation because of their high activity for both RWGS and FT synthesis.⁸¹ Fe catalysts with alkali metal promoters are reported to significantly enhance the selectivity towards long chain hydrocarbons.⁸² These alkali metals, especially K, promote Fe catalysis by weakening the affinity with H₂ and enhancing the adsorption of CO₂ and CO intermediate.⁸³ Different promotional effects were observed by combining a Fe-based MOF catalyst with various elements (Figure 13A).⁸³ K was found to enhance the olefin selectivity drastically from 0.7% to 36% (Figure 13B).⁸³ CO₂ and H₂ chemisorption measurement showed that CO₂ uptake was enhanced while H₂ adsorption was weakened upon K addition, leading to stronger Fe-C interaction and higher selectivity toward olefins. The obtained C₂-C₄ olefin space time yields (STY) of the Fe/C+K(0.75) catalyst was among the best catalyst published (Figure 13C).⁸³

In addition to alkali metals, transition metal components, such as Cu and Co components, were also found to promote Fe-catalysed CO₂ hydrogenation to hydrocarbons.^{84, 85} Cu is known

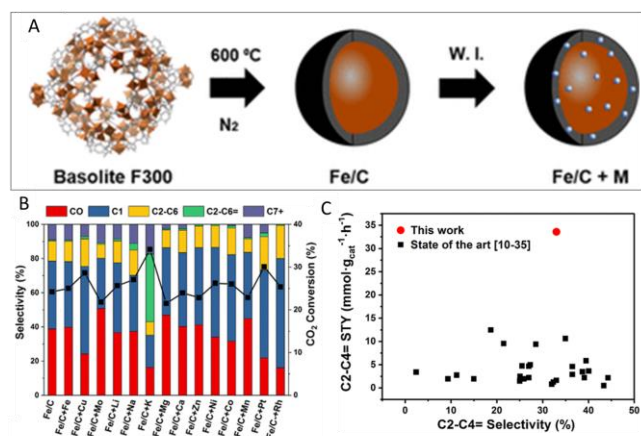


Figure 13. (A) Synthesis strategy for the Fe-based catalysts by carbonization at 600 °C in N₂ and wetness impregnation (W. I.) (B) Effect of different promoters on CO₂ hydrogenation performance. (C) C₂-C₄ olefin space time yields (STY, mmol·g_{cat}⁻¹·h⁻¹) obtained for the Fe/C+K(0.75) catalyst at 350 °C compared to the best catalysts available for CO₂ hydrogenation. Adapted from ref. 83 with permission. Copyright 2018 American Chemical Society.

to be a highly active catalyst for methanol synthesis from CO₂, but when it combines with Fe, it enhances Fe catalysis for both RWGS and CO hydrogenation by suppressing CH₄ formation and promoting C₂-C₇ production.⁸⁴ The catalyst support is also an important factor to increase the selectivity for light olefins. For example, the ZrO₂ supported K-Fe (K-Fe/ZrO₂) catalyst exhibited much higher selectivity to lower olefins than the SiO₂-supported one;⁸⁶ the carbon-coated Fe-catalyst was much better dispersed and stabilized, and was highly active for the CO₂ conversion at atmospheric pressure with higher selectivity to C₂-C₄ olefins.⁸⁷ In addition, methanol has also been studied as a starting precursor for synthesis of olefins. It too requires two reaction steps: CO₂ hydrogenation to methanol and methanol conversion to hydrocarbons as described in recent reviews.^{88, 89}

Despite the great promises demonstrated from thermal reduction of CO₂ to value-added chemicals, these thermal reactions do require the uses of high temperature and high pressure, which makes it challenging to stabilize the catalysts in the reaction conditions and to lower energy consumption.

3.3. Electrochemical Reduction of CO₂

Electrochemical CO₂ reduction reaction (CO₂RR) is an appealing alternative to the thermal reduction for converting CO₂ to value-added chemicals as the reaction can be promoted by renewable electricity under ambient conditions, and be catalysed more selectively by catalyst engineering, as illustrated in Figure 14A.⁹⁰ The electrochemical CO₂RR on the surface of a metal catalyst is generally divided into three steps: CO₂ adsorption, charge transfer, and product dissociation. Each of these three steps plays an important role in controlling catalyst selectivity and final product distribution.⁹¹ The CO₂RR pathways have been studied extensively to explain various products detected from the reaction. Figure 14B is just an example to show these complicated pathways leading to the formation of C₁ and C₂ products.⁹¹ The commonly accepted key reaction

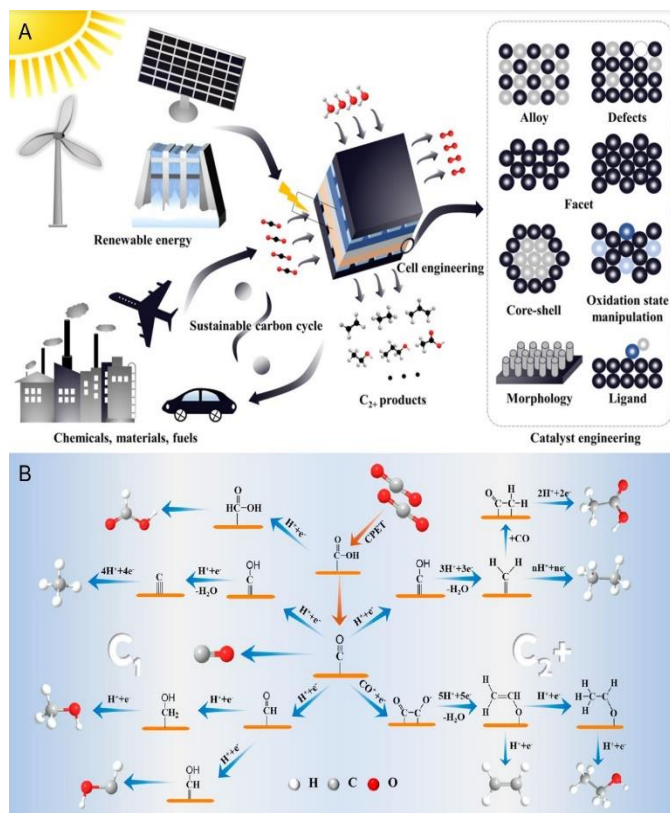


Figure 14. (A) Schematic illustration of sustainable energy cycling based on electrochemical CO₂RR. (B) Proposed pathways to C₁ and C₂₊ products from electrochemical CO₂RR. Adapted from ref. 90, 91 with permission. Copyright 2020 American Association for the Advancement of Science, 2021 American Chemical Society.

steps are CO₂ binding, protonation and reduction to *COOH, which can be further hydrogenated to form formate, or dehydrated to form CO that can either be released from the catalyst surface or function as a key intermediate for next steps of hydrogenation and C–C coupling to C₁ and C₂₊ products. The mechanism leading to the formation of C₁ product is relatively simple. In contrast, the processes leading to C₂₊ products are much more complicated. Recent studies have focused on capturing and identifying the reaction intermediates, such as *COCO, *CHCHO, *COCO, that produce C₂₊ products.⁹²

3.3.1. Metal Nanoparticle Catalysis

Metal nanoparticles with large surface area and controlled surface structures have been studied extensively as catalysts for CO₂RR.^{93–99} Figure 15 summarizes some representative nanoparticle catalysts that are selective for CO₂RR to CO.⁹³ Ultrathin Au nanowires of about 2 nm in width and hundreds of nm in length were found to be among the most active and selective catalyst for the CO₂ reduction to CO.⁹⁹ The CO selectivity is sensitively dependent on the length of the nanowires. The 500 nm Au nanowires showed the on-set CO₂ reduction to CO at -0.2 V (with 37% FE) but reached 94% FE and mass activity (1.84 A/g_{Au}) at -0.35 V. DFT calculation revealed that both COOH and CO preferentially bind to the edge site on the Au nanowires with COOH binding marginally (0.04 eV) stronger than that on the Au(211) edge but CO binding 0.23 eV weaker than that on the Au₁₃ corner, suggesting that nanowire

surface with maximal edge sites facilitates CO₂ reduction to COOH and further to CO.⁹⁹ In addition to Au, Ag, Pd, SnO₂ coated Cu, and Ni–N were also found to be selective in catalysing CO₂RR to CO, as summarized in Figure 15.^{100–103} When Pd, In, Sn, and Bi nanoparticles were employed as catalysts for the CO₂RR, formate (HCOO⁻) was the main product.^{104–107}

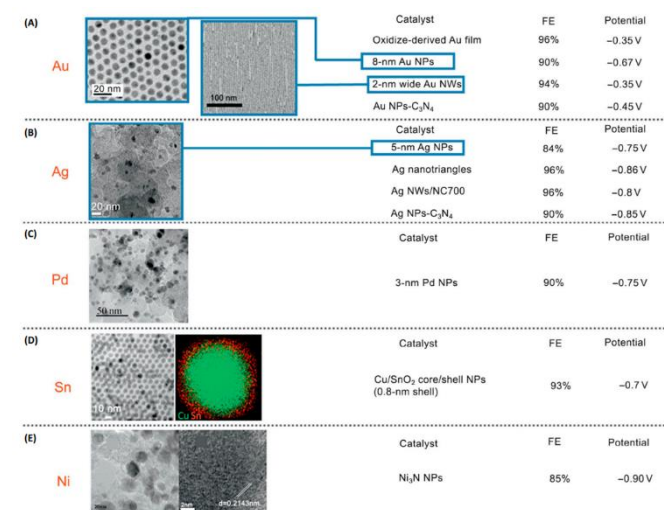


Figure 15. Summary of some representative nanocatalysts based on Au (A), Ag (B), Pd (C), Sn (D) and Ni (E) for electrochemical CO₂RR to CO. All potentials are vs. RHE. NP denotes nanoparticle and FE is the reported Faradaic efficiency. Adapted from ref. 93 with permission. Copyright 2019 Cell Press.

Compared to the formation of CO and formate, selective reduction of CO₂ to C₂ products has been challenging, and Cu has been the major component that is required to catalyse CO₂RR to hydrocarbons.^{92, 95} Recent studies have suggested that the key active components are Cu–Cu₂O mixtures, as observed in the CO₂RR studies on partially oxidized Cu electrode.^{108–111} Cu(I) and residual subsurface oxygen species are considered to play important roles towards enhanced performance. The oxidation state of Cu can be reversibly transformed between Cu(0) and Cu(I) under the electrochemical reaction conditions. The presence of Cu(I) and Cu(0) significantly improves the kinetic and thermodynamic processes of CO₂ activation and *CO dimerization. In situ spectroscopy studies, such as electrochemical liquid transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS) and XAS studies, have shown that the catalyst surface undergoes dynamic structural changes under CO₂RR conditions. For example, over the electroreduction time period, CuO nanosheets were seen fragmenting into smaller species and floating in the liquid layer (Figure 16A).¹¹² In-situ grazing incidence X-ray absorption spectroscopy (GIXAS) and X-ray diffraction (GIXRD) were also used to study thin Cu electrode (50 nm thick) and to characterize the near surface structure of the electrode under the CO₂RR conditions (Figure 16B,C).^{88, 113} It was found that during the catalytic reaction, the surface of the polycrystalline Cu electrode was partially oxidized to Cu₂O. The co-existence of Cu(0) and Cu(I) on the catalyst surface during the CO₂RR was further proven by the operando seconds-resolved X-ray absorption spectroscopy.¹¹⁴ It is now commonly believed that there is a synergistic effect between Cu(0) and Cu(I), which

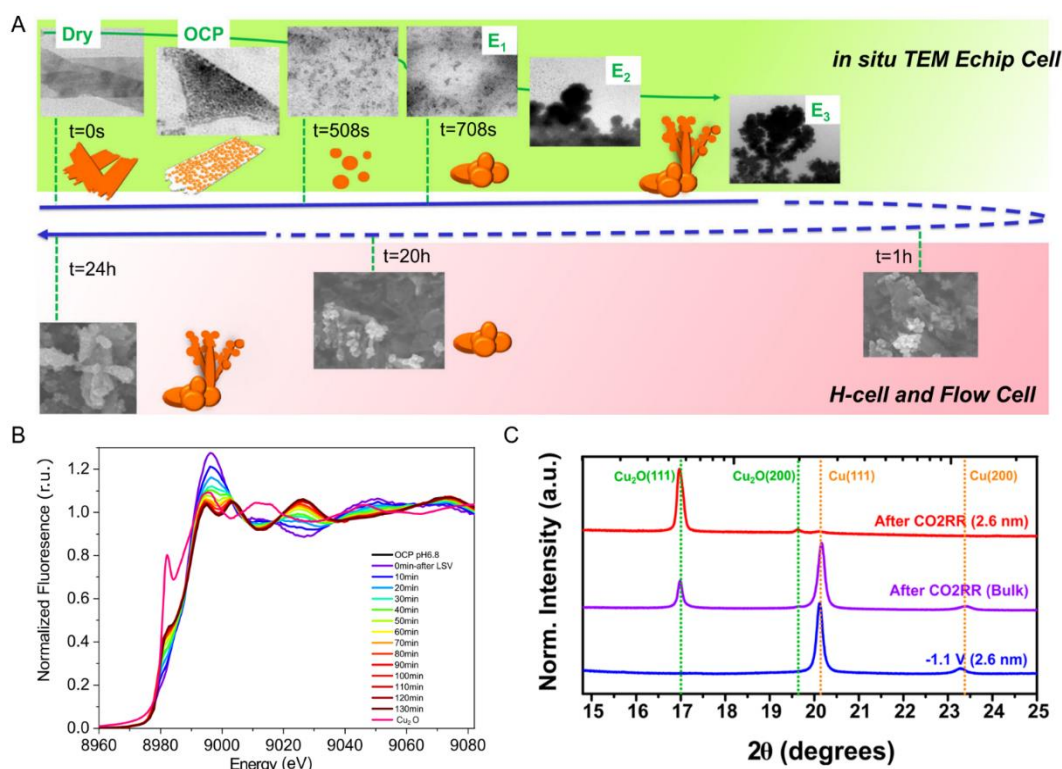


Figure 16. (A) Schematic overview (timeline) of the experimentally observed evolution of the CuO nanosheet morphology probed by the in-situ TEM E-chip flow cell, H-cell, and flow cell electrolyser. (B) XANES at the Cu K-edge of the CuO nanosheet catalyst after CO₂ reduction for different minutes. (C) Grazing incidence X-ray diffraction of Cu(pc) at a probe depth of 2.6 nm before and after releasing the applied potential. Adapted from ref. 112, 113 with permission. Copyright 2020 American Chemical Society and 2021 Nature Publishing Group.

promotes the C–C coupling of intermediates in the reaction process, favouring the formation of C₂+ products. The role of Cu(I) effect on enhancing CO₂RR to hydrocarbons was further supported by the Cu₃N nanocube-catalysed CO₂RR for the formation of C₂H₄ as a major product.¹¹⁵ This high selectivity to

C₂H₄ was attributed to the Cu(I) stabilization by N and Lewis basicity of N on the Cu(100) facet, facilitating C–C coupling and C=O/C–O hydrogenation.

3.3.2. Single Atom Catalysis

Single-atom catalysts, with isolated metal atoms dispersed on conductive carriers, have demonstrated excellent catalytic performance in many chemical reactions. These catalysts integrate the benefits of both homogeneous and heterogeneous catalysts, and provide an ideal platform for optimizing chemical reactions via their easily controllable coordination sites and electronic structures, strong metal-support interactions, as well as their maximal atom utilization. The electrochemical reduction of CO₂ over single metal atom sites can be traced back to the 1970s when cobalt and nickel phthalocyanines were first found to be active for CO₂ reduction.¹¹⁶ Since then, metal–organic complexes with well-defined M–N_x sites have been extensively studied for CO₂RR with high catalytic performance and durability.¹¹⁷ In these M–N_x structures, both C and N coordinated to M also show important synergy effects (via electronic polarization) on the M catalysis to facilitate CO₂ activation and further reactions. For example, C–Zn_xNi_y ZIF-8 catalysts with undercoordinated Ni–N_x sites ($x < 3$) showed much enhanced CO₂-to-CO activity and selectivity than the Ni-phthalocyanine one with well-defined Ni–N₄ sites.¹¹⁸ DFT calculations revealed that the free energy for *COOH formation was lower on the Ni–N_x sites than on the Ni–N₄ sites. This low coordination effect on catalysis enhancement was also

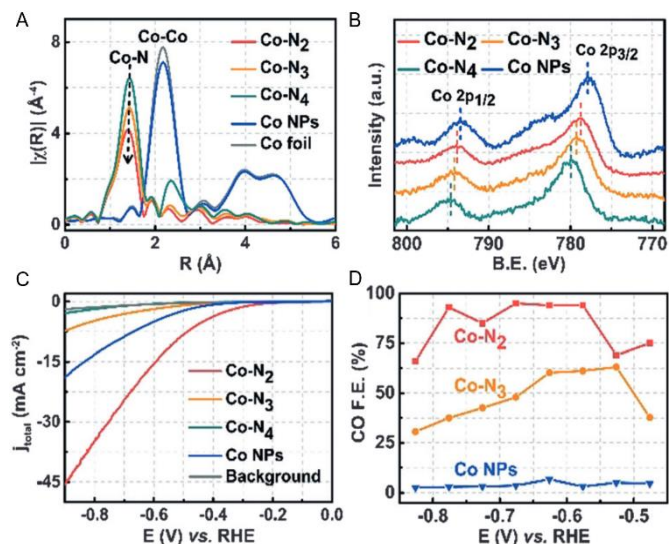


Figure 17. (A) XAS spectra confirm the atomic dispersion of Co atoms in Co–N₂, Co–N₃, and Co–N₄, and suggest the lowest N coordination number in Co–N₂. (B) XPS of all four samples. (C) a) Linear sweep voltammetry (LSV) of Co–N₂, Co–N₃, Co–N₄, and Co NPs and pure carbon paper as background. (D) CO Faradaic efficiencies at different applied potentials. Adapted from ref. 119 with permission. Copyright 2018 Wiley-VCH.

observed from the Co-N catalysts.¹¹⁹ When the Co-N coordination number was decreased from 4 to 2 (**Figure 17A,B**), the Co-N₂ sites showed the best CO₂RR performance with both high activity and selectivity towards the formation of CO (**Figure 17C,D**).¹¹⁹ More and more single-atom catalysts are emerging to show promising catalysis for the CO₂ reduction to C-products beyond CO. These results have been nicely summarized in several recent reviews.^{117, 120, 121}

Up to now, various catalysts have been demonstrated to show promising catalysis for CO₂RR to value-added chemicals under ambient conditions. Their catalysis performance is better understood at atomic scale, and many factors, including atomic composition, atom oxidation states and coordination environment, have been identified as important to improving catalysis activity and selectivity. Despite these advances, controlling catalytic CO₂RR to a C₂₊ product is still a challenging task due to the strong competition from the reaction pathways that lead to the formation of C₁ products. Key factors to maximize C₂₊/C₁ ratios need to be identified, and catalyst structures developed for such catalysis should also stay stable in the CO₂RR condition.

3.4. Catalyst-Electrolyte Interface Engineering for CO₂ Reduction

As electrochemical reactions occur at interfaces of catalysts and electrolytes, and as the CO₂RR needs the presence of protons to form hydrocarbons, interface engineering to control proton concentration and hydrophobicity is equally important for fast binding and reduction of CO₂. Recent advances in surface chemistry and spectroscopy also offer new opportunities to probe reaction mechanisms of CO₂RR at the interfaces and, in turn, guide the design of such interfaces for catalysis enhancement.¹²²⁻¹²⁵ Electrochemical systems that can be used to optimize gas transport,¹²⁶⁻¹²⁹ electrolyte functions,¹³⁰⁻¹³³ intermediate detection,¹³⁴⁻¹³⁹ and reaction pathway engineering,¹⁴⁰⁻¹⁴² have been rapidly developed to improve the overall catalytic performance. In this section, we highlight how interfacial engineering can be applied to optimize electrolyte and catalyst surface ligand effects to enhance CO₂RR catalysis.

3.4.1. pH Gradient, Cation, and Anion Effects

Most electrocatalytic CO₂RRs are operated in an electrochemical reaction system with aqueous electrolyte. The electric double layer formed between the electrolyte and the electrode contains key intermediate species that can dominate mass transport and catalytic evolution process of CO₂.¹⁴³ A number of parameters can be chosen to optimize the electric double layer structure and to control the local environment on the catalyst surfaces, including electrolyte buffer capacity,¹⁴⁴ anion/cation types and concentrations,¹⁴⁵ localized pH,¹⁴⁶ and proton/CO₂ accessibility.^{147, 148} Therefore, the selection of an appropriate electrolyte is of critical importance to tune the CO₂RR activity and selectivity. For example, when operating in an aqueous electrolyte, the reduction of protons, or commonly known as hydrogen evolution reaction (HER), competes with CO₂RR; and it, in turn, lowers the overall electrocatalytic

efficiency towards CO₂RR.¹⁴⁹ However, because of the continuous consumption of proton through proton-coupled CO₂RR and HER, the accumulation of OH⁻ near the surface of a catalyst results in a higher local pH, creating a pH gradient between the interfacial area of the catalyst and electrolyte.¹⁵⁰ The presence of this pH gradient can affect mass transport of different reaction species, such as OH⁻, CO₂, HCO₃⁻ and CO₃²⁻, and as a result, dominate the reactions pathways.^{144, 146, 151}

The CO₂RR selectivity can be improved by increasing the CO₂ concentrations and by inhibiting the HER near the electrode-electrolyte interfaces. Due to the relative low solubility of CO₂ in aqueous electrolyte, a high local pH is required to increase the local CO₂ concentration and to suppress HER.¹⁵² This was better demonstrated when a mesoporous Au-inverse opal (Au-IO) structure served as the catalyst for CO₂RR. In the CO₂RR condition, the partial current density related to CO₂RR was increased with reduction potentials regardless the thickness of the Au-IO film (**Figure 18A**), while that related to HER was decreased initially before increase only slightly at more negative potentials, and, more importantly, the thicker the Au-IO film, the smaller the partial current density (**Figure 18B**).¹⁵³ Here a beneficial pH gradient was created in the pores of the Au-IO film, which enhanced CO₂ adsorption and conversion to CO, but limited proton diffusion and HER (**Figure 18C**).¹⁵³ This was further confirmed by in-situ electrochemical analysis, showing the pH changes near the electrode surfaces.^{150, 154} Another way of promoting CO₂RR is to increase the CO₂ pressure, and therefore the CO₂ concentration, as demonstrated in the Cu-catalysed CO₂RR to ethylene (FE 44%) when the CO₂ pressure was set at 9 atm during the electrolysis.¹⁵⁵ This improved selectivity to ethylene was attributed to the increase in *CO concentration in the initial catalysis steps, promoting *CO-*CO coupling and hydrogenation.

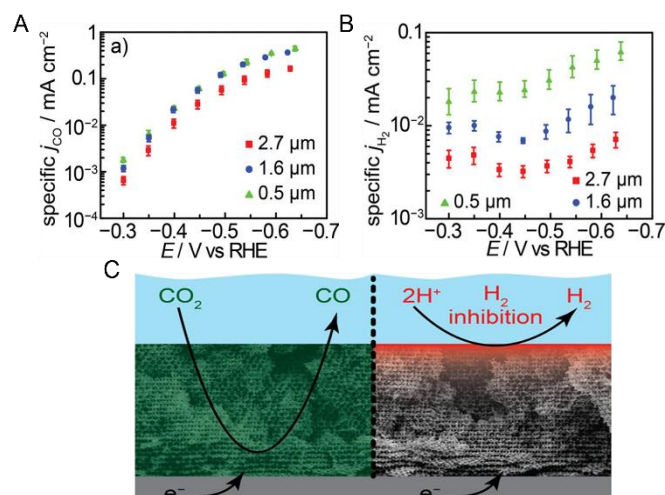


Figure 18. Specific activity for CO (A) and H₂ (B) with different thickness of Au-IO: 0.5 μm (green triangles), 1.6 μm (blue circles), and 2.7 μm (red squares). The samples were evaluated in CO₂-saturated 0.1 M KHCO₃ electrolyte, pH 6.7. Error bars represent standard deviations of three independently synthesized Au-IO samples for each thickness. (C) Scheme represented the mesostructure-induced pH gradient during CO₂RR. Adapted from ref. 153 with permission. Copyright 2015 American Chemical Society.

Metal cations would accumulate near the surface of electrodes under reductive potentials, forming an electric double layer, which could affect the mass transport of CO_2 . As shown in **Figure 19A**, the constructed electrode-electrolyte interface is assigned to the inner Helmholtz plane (IHP) within which intermediate species are populated, and outer Helmholtz plane (OHP) beyond which the hydrated cations are present.¹⁴³ Under a reductive potential, the hydrated cations are attracted to the electrode surface due to the Coulomb attraction, participating in the chemical reactions, modifying catalyst surface electronic structure, and even blocking active sites on the catalyst surface. Therefore, the catalytic performance of a catalyst on CO_2RR can be highly dependent on the electrolyte. For example, when a Ag electrode was studied for CO_2RR to CO, it was found that CO FEs were only around 40% when the Li^+ - and Na^+ -based electrolyte was used as the reaction medium, but the FEs reached 85–90% when the electrolyte contained a larger cation, such as K^+ , Rb^+ or Cs^+ (**Figure 19B**).¹⁵⁶ Compared to smaller cations, which are strongly hydrated, the larger cations are weakly hydrated and more accessible to the surface of the electrode, leading to the decrease in their pK_a and increase in the localized CO_2 concentration. Similar cation size effect was also observed when a Cu electrode was studied for CO_2RR in 0.1 M MHCO_3 electrolyte. Increasing the cation size from Li^+ to Cs^+ in the electrolyte, the FE for H_2 was decreased, but the FE for C_2H_4 and $\text{C}_2\text{H}_5\text{OH}$ was increased (**Figure 19C**).¹⁵⁷ It was believed that the larger cations helped to stabilize the polar species, such as $^*\text{CO}_2$, $^*\text{CO}$, and $^*\text{OCCO}$, more efficiently in the reduction condition, favouring their further coupling and hydrogenation (**Figure 19D**). As a comparison, CH_4 FE was rarely affected by the cation sizes due to the negligible cation interaction with the nonpolar $^*\text{H}$ and $^*\text{CHO}$ intermediate species.

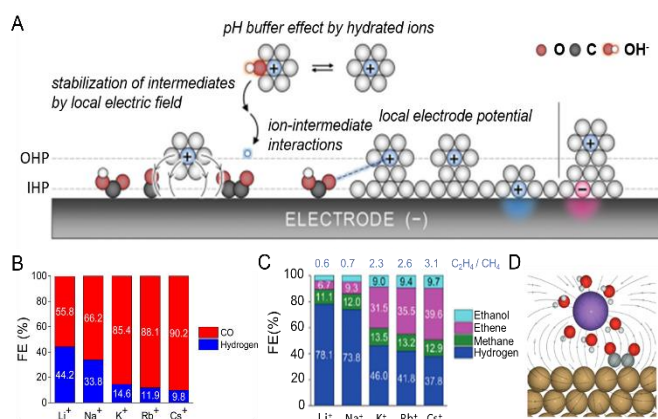


Figure 19. (A) Simplified schematic illustration of the electric double layer composed of the inner Helmholtz plane (IHP) and outer Helmholtz plane (OHP) with chemical equilibria involved. (B) Faradaic efficiencies (FEs) for CO and H_2 produced over Ag at -1 V vs. RHE in CO_2 -saturated 0.1 M MHCO_3 ($\text{M} = \text{Li}, \text{Na}, \text{K}, \text{Rb}, \text{Cs}$) electrolyte. (C) Faradaic efficiencies (FEs) for $\text{C}_2\text{H}_5\text{OH}$, C_2H_4 , CH_4 , and H_2 produced over Cu at -1 V vs. RHE in CO_2 -saturated 0.1 M MHCO_3 ($\text{M} = \text{Li}, \text{Na}, \text{K}, \text{Rb}, \text{Cs}$) electrolyte. (D) Schematic illustration of the local electric field created by cation at the catalyst interface and stabilized OCCO intermediate. Adapted from ref. 143, 156 and 157 with permission. Copyright 2020 Royal Society of Chemistry and 2016, 2017 American Chemical Society.

Similarly, anions in electrolytes can also affect CO_2RR performance of metal catalysts. These anions, for example halides, can function as soft bases to bind to Au and Cu strongly to modify the catalyst surface structure or morphology during the CO_2RR , as demonstrated in the CO_2RR catalysis of the plasma-activated Cu foil.¹⁵⁸ It was found that I^- ions enhanced the reactivity dramatically (lowered the onset potential) as compared to Br^- and Cl^- ions, and the total FE for C_2 - C_3 products (ethylene, ethanol, and propanol) reached 65% at -1.0 V (vs. RHE). I^- ions were thought to be strongly adsorbed on the electrode surface, enhancing the CO_2 binding through the formation of I^- -C bonds. Anions can also regulate the pH change near the catalyst surface, affecting the catalyst's CO_2RR performance.¹⁵⁹

3.4.2. Surface Ligand Effects

Adding ligands on the surface of catalysts offers a powerful way to control the interface of catalyst-electrolyte.¹⁶⁰ The inspiration is from nature where the catalytic efficiency of metalloenzymes heavily relies on the coordination environment of metal sites, e.g., protein frameworks in both first and second coordination spheres. Protein frameworks, despite not being catalytically active by themselves, are an essential component in tuning the activity and selectivity of metal sites. Modifying metal catalysts with surface ligands, therefore, can also enhance electrocatalytic performance toward CO_2RR . Such modification is usually achieved by covalent or non-covalent binding of organic surfactants to metal surfaces.¹⁶¹⁻¹⁶⁴ Surface ligands can boost the intrinsic catalytic activity of metal catalysts by reducing CO_2 activation barriers,¹⁶⁵⁻¹⁶⁷ by changing mass transport during CO_2RR ,¹⁶⁸⁻¹⁷⁰ and/or by defining the local environment to suppress byproduct formation (e.g., HER).¹⁷¹

The common organic ligand used for metal surface modification is thiol in the form of R-SH , where R represents an organic substituent. $-\text{SH}$ has strong bonding affinity with all catalytically active metal surfaces. $-\text{S}^-$ is a softer base than $-\text{O}^-$ and can bind to a Group 10 or 11 metal even more strongly to impact its catalysis for CO_2RR .¹⁷² There have been numerous studies in modifying catalyst surfaces with thiols to improve the CO_2RR selectivity.^{168, 173, 174} One example is to modify a polycrystalline Au film electrode with three different thiols, 2-mercaptopropionic acid (MPA), 4-pyridylethylmercaptan (4-PEM), and cysteine (CYS), and to study the thiol effects on the Au catalysis for CO_2RR .¹⁷⁵ Such modifications did not improve Au catalysis for CO_2RR to CO (the surface coverage generally reduced the Au catalysis selectivity to CO), but they changed other parts of the Au catalysis: the 4-PEM modified Au showed improved selectivity to formate (from 10% FE on Au to 22% on PEM-Au), while the MPA-modified Au showed nearly 100% FE towards H_2 and the CYS-modified Au was more active (not more selective) for generating CO and H_2 . These Au catalysis changes upon the surface modifications were attributed to the proton-induced desorption mechanism associated with pK_a of the thiol ligands, as illustrated in the 4-PEM modified Au catalysis for the improved selectivity to formate (**Figure 20A**), in which 1e^- reduction of pyridine to pyridinium also helped to bind and reduce CO_2 to facilitate the second proton binding to CO_2 and

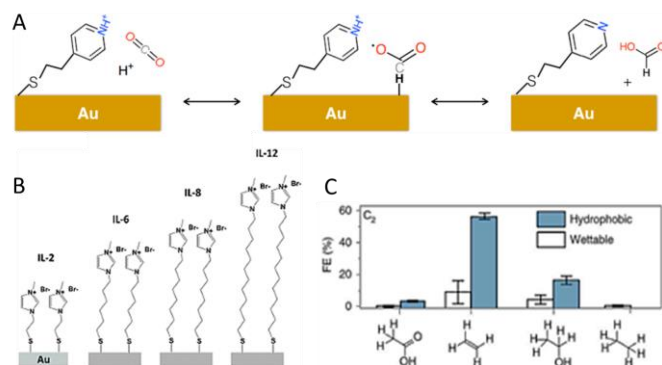


Figure 20. Comparison of partial current density and FE for thiolate ligands on polycrystalline Au: (A) Proposed reaction mechanism of the formate production at 4-PEM and Au interfaces. (B) Schematic of Au electrodes with 1-methylimidazolium-terminated SAMs (IL-2, IL-6, IL-8, and IL-12). (C) FE of C₂ products on both wettable and hydrophobic Cu dendrites at the total current density of 30 mA cm⁻². Adapted from ref. 175, 171, and 168 with permission. Copyright 2017 American chemical society, 2015 Royal Society of Chemistry and 2019 Nature Publishing Group.

its conversion to formate.¹⁷⁶ Not surprisingly, MPA with the smallest pK_a promotes HER.

Another example is to use the thiol-terminated imidazolium to improve Au catalysis for the formation of ethylene glycol (CH₂OH)₂.¹⁷¹ When the Au electrode was modified with different imidazolium-SH ligands (Figure 20B), the Au catalysis showed the ligand length dependent CO₂RR catalysis selectivity with 1-(2-mercaptoethyl)-3-methylimidazolium bromide (IL-2) modified Au exhibiting highest FE (87%) towards ethylene glycol.¹⁷¹ Such enhancement in selectivity to ethylene glycol was attributed to more efficient coupling of imidazolium aldehyde intermediates in the reaction condition. In the presence of a longer ligand chain on the Au surface, the interaction between imidazolium and Au gets weaker, limiting the charge transfer for the formation imidazolium aldehyde intermediates.

Surface ligand modification can also be used to control the microenvironment of catalytic sites and to impact catalysis efficiency. When modifying the catalyst surface with a hydrophobic ligand, the surface area becomes hydrophobic, which allows CO₂ to accumulate, creating a triphasic interface of gas-electrode-electrolyte.¹⁶⁸ For example, when modified with 1-octadecanethiol (ODT), the Cu dendritic surface became superhydrophobic with a water contact angle of 153°. Such a hydrophobic dendrite entrapped more CO₂ near the Cu surface, more efficiently improving the Cu catalysis of CO₂RR to C₂ products (Figure 20C).¹⁶⁸

Amine ligands have also been broadly used not only to stabilize metal NPs in their synthesis but also to modify metal surfaces for catalysis improvement.^{98, 99, 177-181} The presence of amine groups at metal surfaces provides numerous Lewis base centers that can further improve CO₂ adsorption near these metal surfaces via the amine-CO₂ interaction.¹⁸² The amine ligand effect was better demonstrated in a comparative study of Ag catalysis for CO₂RR once a Ag electrode was modified separately with oleylamine (OLA), oleic acid (OA) and 1-dodecanethiol (DDT). The OLA-modified Ag was found to show the highest selectivity to CO (FE 94.2%) across a broad range of

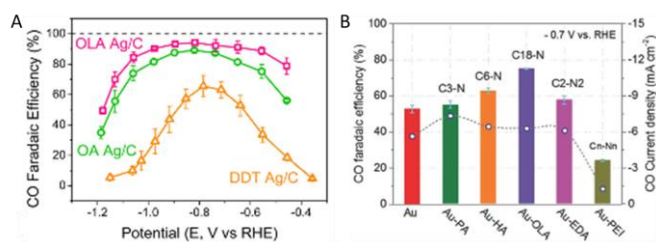


Figure 21. (A) FE_{CO} of OLA-, OA- and DDT-modified Ag NPs supported on carbon black (Ag/C). (B) FE_{CO} (column) and CO current density (circle) of different Au catalysts at -0.7 V (vs. RHE). Adapted from ref. 183, 182 with permission. Copyright 2017 American Chemical Society and 2018 Wiley-VCH.

potentials, while the OA- and DDT-modified Ag demonstrated only 89.1% and 71.0% FE_{CO} respectively (Figure 21A).¹⁸³ In studying amine ligand effect on Au catalysis for CO₂RR, Au NPs supported on graphene oxide (rGO) were grafted with propylamine (PA), hexylamine (HA), OLA, ethylenediamine (EDA) or polyethyleneimine (PEI) respectively.¹⁸² It was found that amines with a linear structures favored the CO₂RR to CO, the longer the chain, the higher the CO FE (Figure 21B).¹⁸² As a comparison, bulky branched amines can block the catalyst active sites and prevent CO₂ from interacting with the metal surface, lowering the CO₂RR selectivity.

Despite the evident effect of these thiols/amines on metal catalysis, the long-standing catalyst stability issue in the CO₂RR condition remains. To stabilize the NP catalysts more efficiently in the CO₂RR condition, N-heterocyclic carbene (NHC) ligand has been introduced.^{162, 164, 184, 185} NHCs bind with metals through the lone electron pair on C to form a strong C-metal σ bond,¹⁸⁶⁻¹⁸⁸ which has been applied to modify surfaces of a variety of metals.^{189, 190} More importantly, the σ -donation of NHCs enriches the charge density on metal surfaces, further promoting metal binding with electrophile CO₂.¹⁸⁶ For example, Au NPs, modified with sterically bulky 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene (Cb) (Figure 22A) showed a much higher FE_{CO} (83%) and current density (7.6-fold) than the plain Au NPs (FE_{CO} = 53%) at the potential of -0.57 V.¹⁶⁴ The tridentate NHC ligand, timtmb^{Me} (Figure 22B) modified Pd electrode showed not only high selectivity for CO₂RR but also stability.¹⁹¹ In the presence of timtmb^{Me}, the Pd catalyst exhibited a larger total current density and positively shifted onset potentials relative to the parent palladium foil (Figure 22C).¹⁹¹ The onset potential for CO₂RR appeared at -0.12 V, which is about 265 mV positively shifted relative to that of the unmodified Pd. The FE of C₁ products increased from the initial 23% to 86% (with timtmb^{Me}, 82% of formate and 4% of CO, Figure 22D) at -0.57 V vs. RHE with a 32-fold increase in current density.¹⁹¹ The tridentate NHC-modified Pd also showed much improved stability as evidenced from the steady product FE in the 6 h electrolysis period.

Metal catalysts modified with polymer NHCs have shown significant catalytic enhancement in CO₂RR. While small molecule ligands can vary the surface properties, polymer ligands form a protective coating layer of 10-50 nm that could "gate" the accessibility of catalytic metal NPs. Monodentate

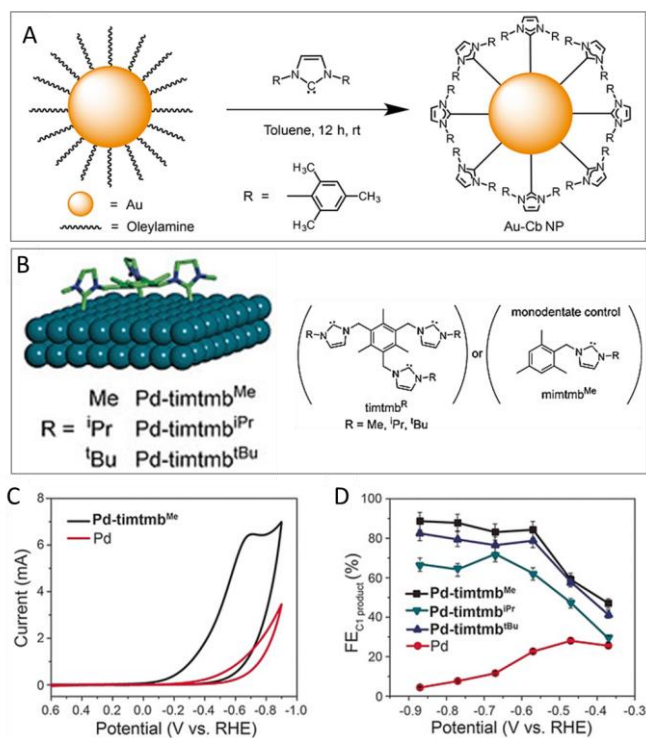


Figure 22. (A) Surface modification of Au NPs with 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene (Cb) through ligand exchange. (B) The CO specific current density (normalized to the electrochemically active surface area) on Au-Cb NP and corresponding Au NP/C at different reductive potentials and corresponding FE of CO and H₂ on Cb-modified Au NPs and corresponding parent carbon supported Au NPs catalysts. (C) Schematic illustration for the tripodal NHC functionalization of Pd surfaces. (D) CV scans of Pd and Pd-timtm^{Me} electrodes in CO₂-saturated 0.5 M KHCO₃ at pH 7.3. (e) FE of C1 products (CO for unmodified Pd; HCOO⁻ and CO for tripodal NHC-modified Pd) on unmodified Pd electrodes and tripodal NHC-modified Pd electrodes at different potentials. Adapted from ref. 164, 191 with permission. Copyright 2016 American Chemical Society and 2018 John Wiley and Sons Ltd.

and multidentate polymer NHC ligands were first studied to stabilize metal catalysts under reductive potentials and to improve the CO₂RR selectivity.¹⁶² The multidentate polymer NHC ligand, poly(vinylbenzyl N-methylbenzyl N-heterocyclic carbene) (PVBMB-NHC₅₇, P1) was synthesized using quaternization of N-methyl benzimidazole with poly(vinylbenzyl chloride) (PVBC). The monodentate NHC-terminated polystyrene (PS₆₅-NHC, P2) was prepared from the end-group functionalization of the halogen-terminated one through atom transfer radical polymerization (ATRP). After cation exchange with KHCO₃, the two imidazolium ended polymers could graft to Au NPs (~14 nm) at relative high grafting density, 1.3 and 0.9 chains per nm² for P1 and P2, respectively (Figure 23A).¹⁶² When catalysing the CO₂RR, the Au-P1/C and Au-P2/C showed both higher activity and selectivity than the Au/C due to their more efficient role in suppressing HER (Figure 23B).¹⁶² The polymer-modified Au NPs also demonstrated much improved stability, as shown in the change of the electrochemical active surface area (ECSA) of Au NPs during a 2 h electrolysis at -0.9 V (Figure 23C).¹⁶² The citrate capped Au NPs showed only 24.7% ECSA retention after the 2 h electrocatalysis, while the polymer NHC-modified Au NPs had ~75% ECSA retention. Even after 11 h electrolysis, the Au-P1/C

still had a FE_{CO} of 86% while the unmodified Au NPs only had <10% FE_{CO} left. The polymeric NHC-binding strategy could be applied to Pd/C (Figure 23D), which showed the desired enhancement in both selectivity (FE_{CO} was increased from 45% to 60%) and stability (ECSA retention was improved from 10% to 91% after 2 h electrolysis).¹⁶² As a control, Pd/C modified with

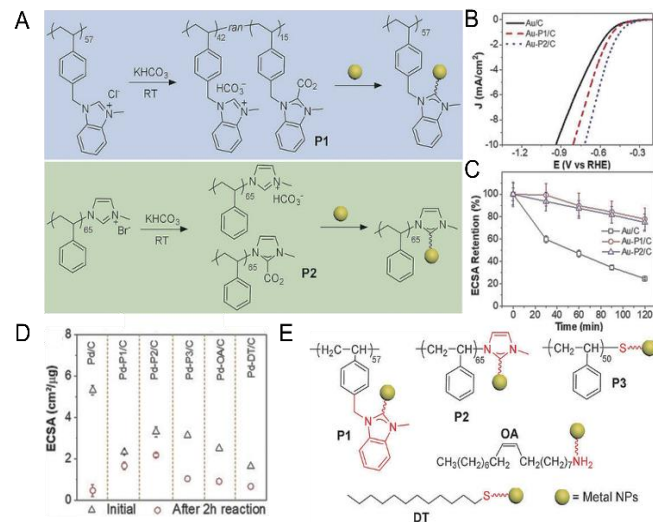


Figure 23. (A) Schematic illustration of Synthesis of P1, P2 and surface modification of NPs (yellow). (B) LSV curves measured in 0.1 M KHCO₃ at a scan rate of 10 mV s⁻¹ for all three samples. (C) ECSA retention at -0.9 V for different electrolysis times of NHC modified Au NPs. (D) ECSA of Pd catalysts before and after CO₂ reduction at -1.26 V for 2 h with various ligands as shown in (E). Adapted from ref. 162 with permission. Copyright 2019 John Wiley and Sons Ltd.

thiol-terminated PS ligands and other ligands (Figure 23D,E)¹⁶² were all less stable than the Pd/C modified with polymer NHC.

Very recently, a nanoparticle/ordered-ligand interlayer (NOLI) was proposed and applied to enhance CO₂RR efficiency.¹⁶⁹ The NOLI structure was created by the collective dissociation of bound ligands (alkylphosphonate) from a dense assembly of metal (Au, Ag or Cu) NPs. Under the reductive potentials, covalently bonded ligands detached but was maintained on the surface through the non-covalent interactions between ligands in the densely packed assembly, as illustrated in Figure 24A.¹⁶⁹ Consequently, this allows K⁺ to transport onto the catalyst surface to balance the overall charge, creating a pseudocapacitive pocket interlayer. Specifically, the ligand chains form a hydrophobic domain around the pocket that facilitates the diffusion of CO₂, while inhibiting the diffusion of water/protons, into the NOLI structure, favouring CO₂ conversion over the HER.¹⁹² The Ag-NOLI improved the activity and selectivity towards CO formation dramatically in CO₂RR, whereas the turnover and selectivity drop to the similar level of Ag foil when the ligand layer was removed (Figure 24B,C), supporting the importance of NOLI structure in the selective CO₂-to-CO transformation.¹⁶⁹ This NOLI structure was demonstrated to be highly active and selective across several metals with up to 99% CO selectivity and onset overpotentials as low as 27 mV. Interestingly, even without strong chemical binding, the ligand density (with respect to the NP surface area) remains relatively stable

throughout electrolysis (Figure 24D).¹⁶⁹ DFT calculations reveal that the specific configuration for the NOLI facilitates the bending of the adsorbed CO₂ molecule, thus promotes the rate

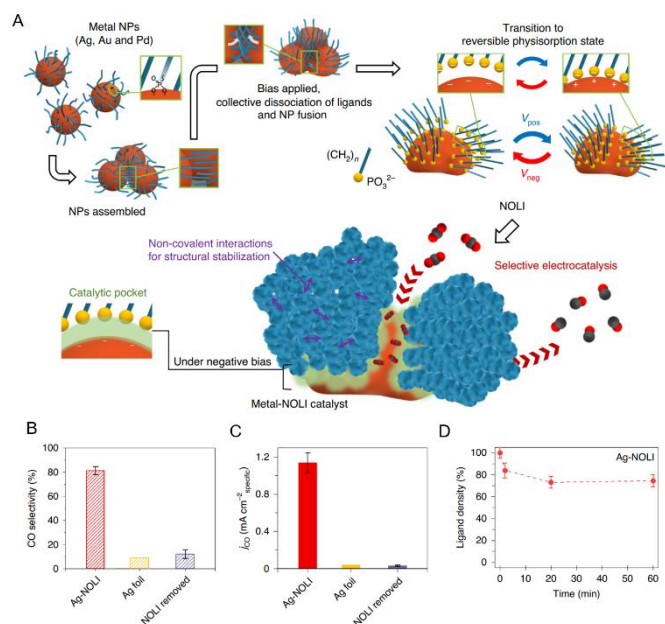


Figure 24. (A) Formation of a NOLI and a metal-NOLI catalyst for selective electrocatalysis. Blue chains on the metal NPs represent chemically bonded alkylphosphonic ligands. Upon applying a negative bias on the assembled NPs, the ligands collectively dissociate from the metal surface during NP fusion and transit to a reversible physisorption state (explicitly shown by the emphasized yellow phosphonate head group). V_{pos} and V_{neg} indicate a positive (anodic) and a negative (cathodic) polarization of the metal particles, respectively. The ligand layer maintains its stability through the non-covalent interactions of the alkyl tails (blue) in an ordered configuration (indicated by the purple double-headed arrows). The resultant metal-NOLI catalyst provides a unique catalytic pocket for selective CO₂ electro-conversion (C, black; O, red). (B) CO selectivity and (C) specific current density of Ag-NOLI, Ag foil and Ag particles after the NOLI is removed from Ag-NOLI, at -0.68 V vs. RHE. (D) Ligand density of Ag-NOLI estimated from XPS throughout CO₂ electrolysis. Adapted from ref.169 with permission. Copyright 2021 Nature Publishing Group.

limiting step of the polarization of non-polar CO₂ with an electron transfer to form the intermediate $^* \text{CO}_2^-$.

4. Coupled CO₂ Capture and Conversion

Both CO₂ capture and CO₂ conversion processes are considered as promising strategies to reduce the CO₂ emission, therefore mitigating global warming and other associated environmental concerns. However, most of the present CO₂ reduction studies, either thermal or electrochemical conversion, are based on pure CO₂ as the feedstock, and there exist large gaps between capture and conversion processes. In a conventional CO₂ capture and conversion process, CO₂ is first captured from either ambient air or flue gas by various capture technologies. Then CO₂ is desorbed, compressed and utilized in preparation of value-added products by chemical reduction reactions.¹⁹³ From the perspective of the whole system, however, the desorption and compression steps are energy-intensive, imposing a large energy penalty to the processes of CO₂ capture and conversion.¹⁹⁴ Therefore the combination of CO₂ capture and conversion has been suggested in a single

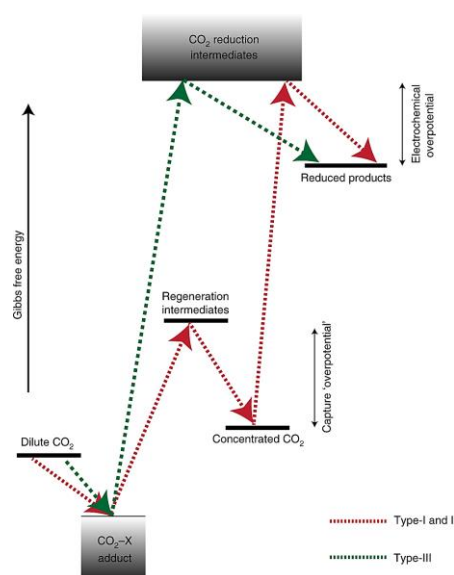


Figure 25. CO₂ capture and conversion energetics for type-I and II (red) and type-III (green). Adapted from ref. 195 with permission. Copyright 2021 Nature Publishing Group.

integrated CO₂ capture and utilization process. The energetics comparison between independent and coupled CO₂ capture and conversion processes are shown in Figure 25.¹⁹⁵ Dilute CO₂ can be captured through the formation of CO₂-X adduct for both processes, however, independent one requires an additional regeneration step to produce pure CO₂ for electrocatalysis, causing an extra capture “overpotential” energy. If both pathways have the same energetic level for CO₂RR intermediates, integrated configurations could achieve lower overall energy requirements due to the energy saving through bypassing the capture media regeneration step. Therefore, integrating the capture and conversion processes is critical to decrease the cost and make the overall process energy efficient.

To date, coupling between CO₂ capture and conversion via thermo- and electro-catalysis has been studied only in a few reports. Therefore, this section summarizes the recent progress made in these two catalysis areas. The integrated capture and conversion was first demonstrated in 2013.¹⁹⁶ In the report, polyamines and amidine bases were used for CO₂ capture in

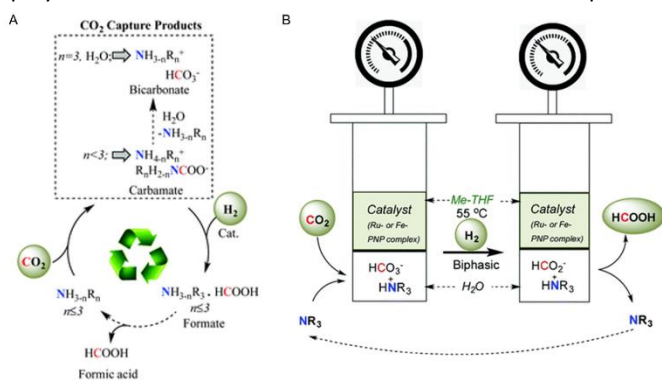


Figure 26. (A) CO₂ capture and conversion to HCOOH. (B) Catalyst recycling by phase separation. Adapted from ref. 197 with permission. Copyright 2016 Royal Society of Chemistry.

alcohol solvents and the capture products were subsequently hydrogenated to obtain alkylammonium formate salts by a Ru-based homogeneous catalyst at 40 bar H₂. The best conversion performance was achieved when CO₂ was captured by 1,5-diazabicyclo [4.3.0] non-5-ene and glycol to form alkyl carbonate, which was then reduced to formate with 55% yield. It should be noted that the captured CO₂ can facilitate the hydrogenation and yield better performance in comparison with equivalent free gaseous CO₂, indicating the CO₂ activation upon capture with amines. CO₂ could also be captured by amines in aqueous media and subsequently converted to alkylammonium formate salts (Figure 26A).¹⁹⁷ The major advancement of this capture/conversion system over the previously reported one is the use of biphasic solvent shown in Figure 26B. CO₂ can be captured as carbamate or bicarbonate in aqueous amine solution, while the catalyst is dissolved in organic solvent. This allows easy separation of the catalyst and formate product, and higher reaction rate due to good solubility of the captured CO₂ in water. The captured CO₂ was selectively converted to formate (up to 95% yield) in the presence of homogeneous Ru- and Fe-based pincer complexes.

Recently, the coupled capture and conversion further led to the synthesis of methanol at a 79% yield.¹⁹⁸ In this process, CO₂ was captured by a short chain polyamine, pentaethylenehexamine (PEHA), to form ammonium carbamate and bicarbonate, which was further hydrogenated at 155 °C and 50 bar of H₂ for 55 h in the presence of a pincer Ru-complex catalyst (Figure 27A). It should be noted that formate and formamide are essential intermediates for amine assisted hydrogenation of CO₂ to CH₃OH. Similarly, alcohol-assisted CO₂ hydrogenation to methanol via formate ester has also been

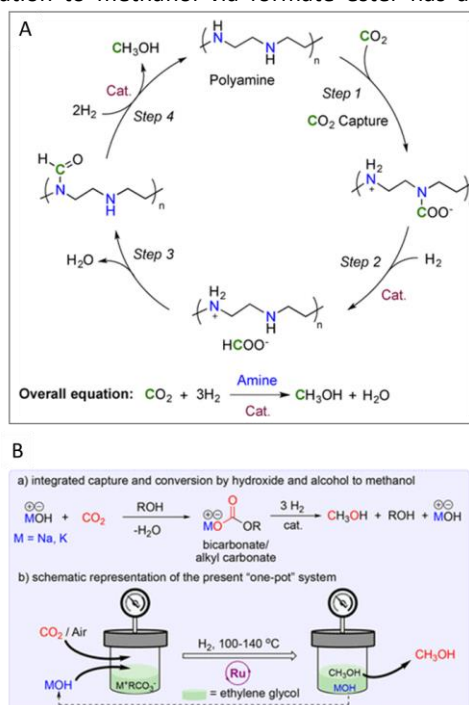


Figure 27. (A) Cycle for CO₂ capture by an amine and conversion to methanol. (B) Integrated CO₂ capture and conversion system. Adapted from ref. 198, 199 with permission. Copyright 2016 and 2020 American Chemical Society.

studied extensively, and was further extended to a new approach of CO₂ capture and conversion to methanol via alkali-metal hydroxides in ethylene glycol (Figure 27B).¹⁹⁹ Different from amines, hydroxides do not suffer from volatility and oxidative degradation issues. More importantly, due to their high CO₂ affinity, these hydroxides have high efficiency for direct air capture of CO₂. In the one-pot system, CO₂ from atmospheric air was efficiently captured by an ethylene glycol solution of KOH to form alkyl carbonate intermediate, which was hydrogenated at 140 °C and 70 bar of H₂ for 72 h to form to methanol at a 100% yield. Such a high yield synthesis of methanol was attributed to the facile hydrogenation of the ester intermediate. Also in the process, hydroxide was partially re-generated and could be used for the next round of CO₂ capture and conversion.

In the case of combining capture and electrocatalysis, CO₂ can be captured by aqueous solution of inorganic hydroxides to yield corresponding bicarbonates. Even though bicarbonate is commonly used as electrolyte for conventional CO₂ electrolysis, it can also serve as the carbon precursor for electrochemical reduction. So far, direct electrolysis of bicarbonate has not been reported yet, but the indirect electrochemical reduction reaction of bicarbonate solution has been achieved using a bipolar membrane (BPM) as the ion-exchange membrane in a flow cell where bicarbonate could be converted to molecular CO₂ due to local acidification.²⁰⁰ Electrolysis of the N₂-saturated 3.0 M KHCO₃ solution yielded CO with a FE of 81% at 25 mA cm⁻², which is comparable to the conventional gaseous CO₂ electrolysis in bicarbonate solution. Similarly, amines were used to capture CO₂ to form carbamate adducts.²⁰¹ Electrolysis of the CO₂ saturated 30% (w/w) monoethanolamine (MEA) aqueous solution led to the formation of formate with FE reaching up to 60.8% in the presence of a porous Pb electrode and

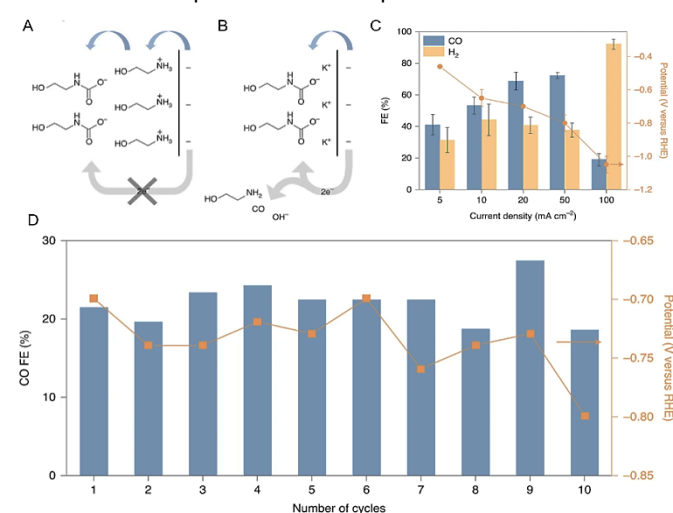


Figure 28. (A) Proposed interfacial structure near the electrode surface. (B) Product distribution of MEA-CO₂ conversion to H₂ and CO at different applied current densities, ranging from 5 mA cm⁻² to 100 mA cm⁻² in a flow cell system. The error bars represent the standard deviation of three independent measurements. (C) Recycling performance of the 2 M MEA with 3 M KCl electrolyte at a constant applied current density of 10 mA cm⁻² heated to 30 °C in a three-electrode configuration. Products were collected within 1 h. Adapted from ref. 202 with permission. Copyright 2021 Nature Publishing Group.

cetyltrimethylammonium bromide. One challenge associated with the direct electrolysis of carbamate is the electrostatic repulsion between carbamate ion and the cathode surface. To address this issue, an alkali cation could be added into the aqueous MEA solution to change the interfacial structure near the electrode, thereby improving the electron transfer from the electrode to the carbamate and the electrochemical performance as shown in **Figure 28A-B**.²⁰² For example, adding 2 M KCl as supporting electrolyte and by using Ag as a catalyst, CO was formed at 72 % FE and a current density of 50 mA cm⁻² (**Figure 28C**). The amine electrolyte was recycled 10 times and could still be used for the capture and conversion reaction without obvious FE_{CO} drop, demonstrating the promising stability of the electrolyte for continuous CO₂ capture and conversion (**Figure 28D**).

5. Concluding Remarks

A sustainable carbon cycle is essential for maintaining the healthy evolution of life globally. However, human activities, especially the ever-demanding energy consumptions, have led to excessive depletion of fossil fuels, and severely affected the well-established equilibrium of the carbon cycle in nature. Given the threat of excessive CO₂ emission, there is now a growing demand for negative carbon technologies. Carbon capture and storage as well as direct air capture are the promising technologies that could be utilized to minimize and/or reduce CO₂ emissions. Various adsorbent materials have been developed for CO₂ capture, including aqueous hydroxides, solid alkali carbonates, organic amines, and porous materials. To date, the investigations of direct air capture adsorbents have focused more on the use of solid-supported amine materials for improved stability and recyclability. The chemical reactions between CO₂ and amines ensure significant CO₂ uptake even at low CO₂ partial pressures with much higher selectivity. The physical adsorption strategy using porous materials is also considered as an attractive alternative to conventional chemical adsorption approaches. Moreover, the modification of metal centres, functional groups as well as pore sizes could incorporate both chemisorption and physisorption capability within one adsorbent structure and in turn offer better CO₂ adsorption capability and selectivity. Looking into the future, practical CO₂ adsorbent materials that are highly active, selective, recyclable, and cost-effective are still in demand.

The reduction of CO₂ into value-added chemicals and fuels is equally important to carbon neutral and sustainable energy. Thermal catalysis of CO₂ hydrogenation has been attractive because H₂ can be generated from water electrolysis by renewable energy. However, this method does require high temperature and pressure for the conversion to complete. Electrochemical CO₂ reduction, in comparison, can be initiated by renewable electricity under ambient conditions. To lower the activation energy barrier of CO₂ and to convert CO₂ to value-added chemicals, active, selective, and stable catalysts need first to be developed. Catalyst-electrolyte interfaces should also be well-engineered to eliminate all interfacial and mass transport issues during the reaction. Despite the great advances

made in these areas, the development of efficient catalysts still posts some serious challenges for practical applications.

Integrated CO₂ capture and conversion removes the cost of CO₂ release and compression and could potentially improve the overall energy efficiency of the system. Recently, the feasibility and potential benefits of the integrated CO₂ capture and conversion systems have been demonstrated. But still, there is much to do in research and development to uncover the fundamental mechanisms that lead to efficient transformation of the captured CO₂ to the targeted carbon products. Once the new catalysts and the reduction processes are materialized, coupling CO₂ conversion with direct air capture will become a true integrated technology for realizing negative CO₂ emission and energy sustainability.

Author Information

Corresponding author

* E-mail: jie.he@uconn.edu; ssun@brown.edu

Biographies

Kecheng Wei received his B.S. degree (2017) in Chemistry from University of Science and Technology of China. He joined Prof. Shouheng Sun's group in 2017 and is currently a Ph.D. candidate in the Chemistry Department of Brown University. His research is in the shape-controlled synthesis of nanocatalysts for fuel cell reactions and CO₂ reduction.

Huanqin Guan obtained his B.S. degree from Peking University in 2018. He then joined Pro. Shouheng Sun's group and is currently a Ph.D. candidate in the Chemistry Department at Brown University. His research interests involve nanocatalyst synthesis and their applications in green chemistry reactions, and CO₂ capture and conversion.

Qiang Luo received his B.S. degree in Material Science and Engineering from Shaanxi Normal University in 2019. Currently he is a Ph.D. student at the Department of Chemistry at the University of Connecticut under the supervision of Prof. Jie He. His research interests include the synthesis and applications of mesoporous materials and CO₂ reduction.

Jie He earned his B.S. and MS degrees in Polymer Materials Science and Engineering from Sichuan University and his Ph.D. in Chemistry from Université de Sherbrooke in 2010. After working with Professor Zhihong Nie as a postdoctoral fellow at the University of Maryland, he joined the faculty of the University of Connecticut where he is currently an Associate Professor of Chemistry. His group focuses on the design of hybrid materials of polymers and inorganic materials (metal ions, clusters, and nanoparticles) being capable of catalyzing the activation of H₂O, O₂ and CO₂ as inspired by nature.

Shouheng Sun received his Ph.D. in Chemistry from Brown University in 1996. He joined the IBM T. J. Watson Research Center (Yorktown Heights, New York) first as a postdoctoral fellow (1996-1998) and then as a research staff member (1998-2004). In 2005, he returned to Brown University as a tenured Associate Professor and was promoted to full Professor in 2007. He is now the Vernon K. Kriebel Professor of Chemistry and Professor of Engineering. He served as Associated Editors of the

Royal Society of Chemistry Journals *Nanoscale/Nanoscale Advances* (2012-2021) and is the Fellow of the Royal Society of Chemistry. His main research interests are in chemical synthesis and self-assembly of nanoparticles for catalytic, magnetic, and biomedical applications.

Conflicts of interest

There are no conflicts of interest to declare.

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