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Advanced catalytic strategies for CO₂ to methanol conversion: noble metal-based heterogeneous and electrochemical approaches

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The next generation is threatened by climate change, the significant impacts of global warming, and an energy crisis. Atmospheric CO₂ levels have surpassed the critical 400 ppm threshold due to significant reliance on fossil fuels to satisfy the increasing energy demands of our fast-progressing society. An overabundance of manufactured carbon dioxide (CO₂) emissions severely disrupts the ecology. The synthesis of methanol by the selective hydrogenation of CO₂ is a viable approach for generating clean energy and sustainably safeguarding our biosphere. Methanol is a versatile molecule with several uses in the chemical industry as an alternative to fossil fuels. The methanol economy is recognized as a pivotal development in the pursuit of a net zero-emission fuel, representing a crucial stride toward a more sustainable planet. The developing green methanol industry, or renewable methanol initiative, primarily relies on CO₂ adsorption and usage. This novel technique is essential for mitigating global warming. This review focuses on the synthesis of methanol utilizing noble metal-based catalysts and electrochemical reduction methods, examining the associated thermodynamic challenges and outlining future directions for research. It emphasizes the role of noble metals, including palladium, gold, silver, and rhodium, in enhancing catalytic activity and selectivity during the CO₂ to methanol conversion process. The incorporation of these sophisticated catalytic processes improves methanol production efficiency and facilitates novel methods for carbon capture and usage, therefore advancing a more sustainable energy framework.

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Sustainability spotlight

A perspective on noble metal-based catalytic conversion of CO₂ to methanol through heterogeneous and electrochemical approaches presents a promising solution to address the increasing concerns regarding climate change. The current situation is critical: CO₂ emissions from industrial activities constitute a significant contributor to global warming, and elucidating efficient methods for converting CO₂ into valuable products is crucial for achieving sustainable development. Noble metal catalysts play a pivotal role in enhancing the selectivity, efficiency, and stability of CO₂ reduction reactions. The sustainable advancement of this research lies in optimizing these catalysts to facilitate CO₂ conversion at reduced energy inputs, thereby rendering the process more cost-effective and scalable for industrial applications. This research aligns with SDG 7 (Affordable and Clean Energy) by enabling the production of methanol as a clean fuel, SDG 9 (Industry, Innovation, and Infrastructure) through the development of advanced catalytic technologies, and SDG 13 (Climate Action) by addressing the reduction of CO₂ emissions and advancing climate solutions.

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1. Introduction

The use of fossil fuels has ushered in an era of extraordinary wealth and improved living standards for humanity.^{1,2} However, excessive fossil fuel burning for energy generation elevates the emission of anthropogenic greenhouse gases (GHGs), mostly in the form of pollutant CO₂. According to the International Energy Agency (IEA), Global Energy & CO₂ Status Report, in 2022 the worldwide CO₂ emissions will have peaked at about 36.8 Gt a new all-time high, and the current concentration of atmospheric CO₂ is approximately 421 ppm, which has increased by 50% since the beginning of the industrial age.³ The massive release of CO₂ to the environment disrupts the Earth's natural



carbon cycle and global ecology, leading to substantial and feasibly irreversible changes in the world's climate such as global warming, ocean acidification, and sea level rise, which have a direct consequence on human health.⁴⁻⁷ Green carbon science is the study and optimization of effective carbon resource processing, utilization, and recycling for lowering CO₂ emissions, lessening the greenhouse effect, reducing reliance on fossil fuels, and lowering the global carbon footprint.⁸⁻¹³ Therefore, the creation of clean energy technology is the only option for the next generation.¹⁴⁻²⁰ In that sense, one of the main research focuses in energy engineering is the regulation and utilization of CO₂.²¹⁻²⁹ In fact, recent years have seen the development of carbon capture and storage (CCS) technologies, which separate CO₂ from combustion byproducts or chemical processes for subsequent recycling or storage.³⁰⁻³⁵ Direct capture of CO₂ from the atmosphere has garnered scientific and practical attention in recent times.³⁶⁻⁴⁶ Despite reducing CO₂ emissions to a certain degree, CCS is not a viable long-term solution due to its exorbitant expense and the possibility of leakage.⁴⁷⁻⁵³ Internationally, there are currently 20 active large-scale carbon capture and storage (CCS) facilities that annually separate around 40 million metric tons of carbon dioxide (CO₂) and store it underground⁵⁴⁻⁶⁰ (The Global Status of CCS; (Global CCS Institute: 2020)). However, this amount represents only 0.1% of the total global carbon emissions. However, the majority of these CCS projects fall under the category of enhanced oil recovery (EOR), which involves injecting CO₂ underground to assist in extracting fossil fuels with the aim of creating a financially viable business model.⁶¹⁻⁶³ The price for CO₂ sequestration from a power plant ranges from \$60 to \$100

per metric ton of CO₂, excluding storage and transportation expenses.⁶⁴⁻⁶⁸ Therefore, the implementation of EOR is essential to ensure the economic feasibility of CCS, which in turn leads to the introduction of more fossil fuels into the carbon cycle.⁶⁹⁻⁷³ For CCS to have a significant influence on climate change, it must be commercialized through the development of cost-effective and energy-efficient systems.⁷⁴⁻⁸² Systems must ensure that the cost of producing CO₂, regulated by authorities, exceeds the cost of capturing and storing it. This will help create an artificial carbon cycle. Additionally, we need to turn CO₂ into chemicals and fuels that are in high demand (Fig. 1).^{83,84} This will serve to effectively utilize a significant portion of the surplus global CO₂. Currently, around 230 million tons (Mt) of carbon dioxide (CO₂) are utilized annually, as reported by the IEA in 2019.^{85,86} However, CO₂ usage represents less than 1% of overall CO₂ emissions.^{87,88} Currently, the market size limits the conversion of CO₂ into chemicals. Thus, the catalytic hydrogenation of CO₂ into value-added products is a key method for CO₂ utilization, leading to the production of carbon-based substances such as methanol, dimethyl ether, formaldehyde, urea and various hydrocarbons.⁸⁹⁻⁹⁵ Among the products stated above, methanol (CH₃OH) is a significant chemical feedstock that can be utilized as an alternative chemical for fossil fuels in internal combustion engines, fuel cells, and the production of formaldehyde, methyl-*tert*-butyl ether (MTBE), acetic acid, alkyl halides, *etc.*⁹⁶⁻⁹⁸ According to the well-accepted hypothesis of Olah in a book titled "Beyond Oil and Gas: The Methanol Economy," methanol may be indispensable in the near future, and CO₂ hydrogenation is one of the most promising and regenerative routes for methanol synthesis.⁹⁹ The elevated



Fig. 1 Overview of key methanol synthesis methods using diverse carbon sources.



volumetric energy density of methanol renders it a feasible substitute for gasoline in internal combustion engines (ICEs), enhancing the octane rating. Moreover, in comparison to traditional gasoline internal combustion engines, methanol internal combustion engines produce markedly lower emissions of contaminants. The Indian government has been actively encouraging the adoption of clean transportation and the use of fuel-cell vehicles.¹⁰⁰ In 2012, the Dor Group initiated pilot testing following the decision by the Israeli government to explore alternative methods of reducing dependence on traditional fuels. One of the most promising approaches identified was the utilization of methanol as a substitute for petrol or as a component in petrol blends for internal combustion engines (Dor Group, 2019). China is also rapidly advancing the development of the methanol fuel market.

It is crucial to note that the hydrogen generated *via* water electrolysis can function as a long-term storage solution and be directly transferred to required locations for usage as a transportation fuel or in industrial applications. Moreover, hydrogen can be converted into electrofuels following the power-to-X concept, thereby storing renewable electrical energy within the chemical bonds of gaseous or liquid fuels.^{101,102} Methanol can function as a carbon-neutral electrofuel when synthesized from hydrogen *via* electrolysis and carbon dioxide sourced from atmospheric capture, biomass, or industrial emissions^{103,104} (Fig. 2). Methanol is a prominent and extensively traded chemical commodity, with the global methanol market projected to expand at a compound annual growth rate (CAGR) of 4.50% from 2022 to 2028.^{105,106} In the chemical industry, methanol is used as both a feedstock and an energy carrier. Its applications range from organic transformations to sustainable

energy solutions, highlighting its importance in both traditional and emerging chemical processes. Methanol can function as a C1 source to facilitate various C–C and C–N bond formations and dehydrogenative coupling reactions, which are significant in the realms of natural product synthesis and drug development.^{107,108} For instance, methanol is crucial for the production of formaldehyde, methylamine, methyl halides, methyl ethers, methyl esters, dimethyl ether, and acetic acid. It is additionally used in the manufacture of pharmaceuticals, biomolecules, agrochemicals, and polymers. Methanol may be transformed into olefins such as ethylene and propylene, which serve as essential building blocks for the petrochemical industry.^{109,110} Furthermore, methanol serves as a versatile compound with applications as a solvent and/or additive in diverse industries, including paint removal, windshield washing fluids, and as a fermentation substrate in microbial production processes.¹¹¹

In this context, it is noteworthy to mention that homogeneous (organometallic catalysts, metal-free catalysts, and N-heterocyclic carbenes) and heterogeneous catalyst systems have recently been successfully developed, and they are excellent candidates for hydrogenation of CO₂ to produce methanol.^{112–123} Another highly appealing strategy extensively studied by the scientific community is the direct electrocatalytic carbon dioxide reduction reaction (ECO₂RR).^{124–126} In this instance, the term “direct ECO₂RR” denotes the complete conversion of CO₂ to a specific product, methanol, at a single electrode.^{127–129} In electrocatalytic technology, customized catalysts can improve electrode interface reaction kinetics.^{130,131} It lowers activation energy and helps electrolyte reactants move electrons.^{132,133} Electrocatalysts accelerate electron transit from



Fig. 2 Various approaches for converting CO₂ to CH₃OH.



noble metals to other materials by lowering voltage.^{134–138} To improve performance, researchers strive to augment the number of active sites and elevate the intrinsic activity of these sites. This involves fine-tuning the electronic and structural properties of the active sites to improve their catalytic efficiency.¹³⁹ Recent methodologies exploit local electrostatic fields to enhance the adhesion of electrode surfaces for intermediates, facilitating proton transfer to electron-rich active species and enabling the electrochemical reduction of CO₂ to produce methane.¹⁴⁰ In another study, Zhou *et al.* reported the O-philic adsorption strategy to facilitate the electrosynthesis of urea.¹⁴¹ This study enhances our comprehension of how to control the properties of reactant adsorption–desorption dynamics for targeted conversion pathways within a comprehensive reactive multistep process pertinent to diverse electrocatalytic applications.

The first commercial methanol production unit was established in Anyang, Henan Province, China. Here methanol was synthesized using the waste carbon dioxide and hydrogen gases.¹⁴² This process used the Emissions-to-Liquids (ETL) technology which was initiated by Carbon Recycling International (CRI) and the first pilot plant was established in Iceland.¹⁴³ Another emerging technology in the methanol economy is the CAMRE process, jointly developed by the Korea Institute of Science and Technology and POSCO.¹⁴⁴ Carbon Recycling International developed a pilot plant for the commercial synthesis of methanol from CO₂. In this, the source of CO₂ is the Orka geothermal power plant and hydrogen is generated from the electrolysis of water from the Icelandic power grid and the methanol production capacity is 4000 tons per year. Blue Fuel Energy (BFE) is Canadian Methanol Corporation's conventional methanol production unit which produces methanol and gasoline based on the MTG process. Emerging techniques for producing methanol from CO₂ include photocatalytic conversion, electrochemical reduction, photoelectrochemical reduction, chemical conversion and plasma reactor technologies.^{145–154}

A large number of metal-based catalysts have been employed for methanol synthesis, but the most popular catalyst in CO₂-derived methanol synthesis is Cu/ZnO/Al₂O₃.^{23,155–161} The major drawback of Cu based catalysts is their pyrophoric properties and low stability arising from sintering and agglomeration enhanced by the generation of water and mobility of ZnO.^{156,162–165} This review focuses on the synthesis of CH₃OH from the hydrogenation of CO₂ by employing noble metal based heterogeneous catalysts. The main advantages of noble metal-based catalysts are their excellent stability and resistance to the sintering effect, making them alternatives to Cu-based catalysts.^{166–170} An efficient heterogeneous catalyst possesses moderate binding strength with the reactant and intermediate.^{171–174} The success of catalytic reactions depends on the identification of the active site, accompanied by an understanding of structure–activity relationships that derive catalytic descriptors to explain the catalysis.^{175–179} Current research emphasizes that noble metal-based catalysts are superior for the conversion of CO₂ to CO *via* the so-called reverse water gas-shift (RWGS) reaction with high reaction rates and high selectivity.^{180–184} Noble metal catalysts are

excellent for CO₂ hydrogenation due to their unique electronic and structural properties, specifically their unique tunable d-band centers.^{185–190} The d-band center mainly represents the energy level of the d-electrons relative to the Fermi level, strongly influencing the adsorption and activation of reactants such as CO₂ and H₂.^{191–193} The alignment of the d band center with the Fermi level enhanced the catalytic activity by optimizing the binding strength of intermediates.^{194,195} Pd exhibits an intermediate d band center, effectively balancing CO₂ activation and methanol desorption.^{158,196} In contrast, Au with a lower d band center reduces the strong binding of intermediates, which enhances selectivity. Experimental evidence suggests that Pd based catalysts show high turnover frequencies (TOFs) and methanol selectivity compared to non-noble metals owing to their superior activation energies and adsorption energies.^{197–199} So, the manipulation of d band centers enhances the catalytic performance by tailoring the adsorption energies.^{200–202} It has been a widely accepted strategy to manipulate the²⁰³ d-band center of noble metals integrated with other metal compounds such as metal oxides/hydroxides and carbides by the electronic effect, which influenced the interface of atomic rearrangement with the geometric effect and strain effect.²⁰⁴ The catalytic reaction mainly occurs at the interface such as the metal–metal interface, metal–porous material interface or metal–metal oxides/hydroxides/carbides interface which leads to enhanced the catalytic activity of hydrogenation of CO₂.^{205,206} The synthesis strategy of noble metal based heterogeneous catalysts with a proper understanding of structure–property relationships such as the active site of the catalyst, morphology, composition, strain, metal support interaction, crystallinity, defects *etc.* is one of the great achievements of the energy engineering sector.^{185,207,208} A promising strategy should be adopted for utilizing noble metal-based catalysts. In this respect, the strategy of incorporating bulk metals into nanostructure supported catalysts boosts the cost-effective industrial production of methanol.

Recently, several excellent reviews have been published and paved the way to catalytic CO₂ conversion to value-added chemicals.^{209–214} However, the main aim of this comprehensive review is the hydrogenation of CO₂ to CH₃OH using heterogeneous noble metal-based catalysts with an electrochemical approach. This review first focuses on the physical and chemical properties of CO₂ with thermodynamic considerations. Then we have briefly addressed various approaches to the catalytic conversion of CO₂ to CH₃OH such as the homogeneous approach, heterogeneous approach, photocatalytic approach, and electrochemical conversion approach, summarizing the catalytic journey of CO₂ to CH₃OH. The mechanism of the conversion of CO₂ to CH₃OH is one of the interesting sides of this article. Then the progress of noble metal-based heterogeneous catalysts is deeply discussed with structure–property relationships. We also provide an overview of the electrochemical reduction approach for the conversion of CO₂ to CH₃OH. The challenges and possibilities of CO₂ reduction for industrial applications are also included. Finally, we have included the future scope and perspectives of methanol synthesized from CO₂.



2. Physicochemical nature and activation of CO₂

A CO₂ molecule in its neutral state belongs to the $D_{\infty h}$ point group and has a linear structure, with a bond length between carbon and oxygen of 1.17 Å. Because of the electronegativity differences, the net electronic structure of the molecule can be represented as $O^{-\delta}-C^{+2\delta}-O^{-\delta}$.²¹⁵ In light of this, bifunctional catalytic sites are required to activate the C–O bond in an efficient manner, as the C atom is electrophilic and the O atoms are nucleophilic.²¹⁶ The highest occupied molecular orbital (HOMO) of CO₂ is located on the more electronegative oxygen atoms, whereas the lowest unoccupied molecular orbital (LUMO) is composed of the hybrid orbitals. The reduction of carbon dioxide (CO₂) introduces an electron into its LUMO. This results in the molecule undergoing a conformational shift to accommodate the energy differences between each orbital, thereby enhancing its ability to interact with nucleophiles. Simultaneously, the localized electron density of oxygen lone pairs allows the HOMO to interact with electrophiles. As a result, a meta-stable radical adduct (CO₂^{•-}) is generated in a bent shape that is kinetically stable (an activation energy barrier of ~0.4 eV) with an average lifetime of 60–90 μs. The common metal center (metal oxide), which is usually used for CO₂ reduction, where CO₂ is physisorbed, exhibits several coordination modes, such as monodentate, bidentate, or even tridentate, depending on the surface atomic arrangement.²¹⁷

3. Conversion of CO₂ to methanol: thermodynamic aspects

In the present era, syngas (CO and H₂ mixture) is one of the main resources for the commercial production of methanol. In methanol synthesis, the H/C ratio is crucial, so to balance this ratio, a small amount of CO₂, *i.e.* 2–8% is added to the CO/H₂ mixture to enhance the reaction rate.²¹⁸



Reverse water gas shift (RWGS) reaction:



The processes of making methanol from CO₂ hydrogenation and the RWGS reaction are limited by thermodynamics. As the reaction temperature increases, the CO₂ conversion rate drops. It is important to note that the synthesis of methanol from CO₂ is an exothermic process that competes with the RWGS reaction, an endothermic reaction. According to Le Chatelier's principle, high pressure and low temperature thermodynamically favor CO₂ conversion to methanol. But considering the chemical inertness of CO₂, a higher temperature makes CO₂ activation easier for methanol production, but it can also lead to increased selectivity towards the undesirable RWGS reaction thermodynamically to produce CO and H₂O. In this way, the RWGS process not only

consumes hydrogen but also lowers the CO₂ equilibrium conversion rate, hence reducing the generation of methanol.⁷⁰ It was observed that less than 40% methanol was obtained from CO₂ at 200 °C but at the aforesaid temperature, more than 80% yield was obtained from the syngas process. Therefore, high pressure and lower temperature are required to control the RWGS process²¹⁹ (Fig. 3). According to the reaction (eqn (1)), as compared to the syngas strategy, methanol synthesis from CO₂ hydrogenation requires an additional quantity of hydrogen for the removal of one oxygen atom from CO₂, yielding water as a by-product (eqn (2)).²²⁰ It is important to note that water, a byproduct of both processes, enhances catalyst sintering. This phenomenon deactivates the catalyst and reduces the efficiency of subsequent steps in methanol production.²²¹ Therefore, the foregoing explanation implies that thermodynamic equilibrium limits the maximum methanol yield; nevertheless, the equilibrium constraint on methanol yield may be bypassed by optimizing reaction conditions, activating the catalyst, using promoters, developing new reactor designs, *etc.*^{222,223}

However, if we take into account the CO₂ thermodynamic potential, the following reduction reactions occur:



Fig. 3 (a) Free energy of methanol synthesis (MS) from CO₂, RWGS and syngas hydrogenation (COH). (b) Equilibrium conversion-selectivity values of the CO₂-hydrogenation reaction at various pressures. Reprinted with permission from ref. 156. Copyright 2020 Royal Society of Chemistry.



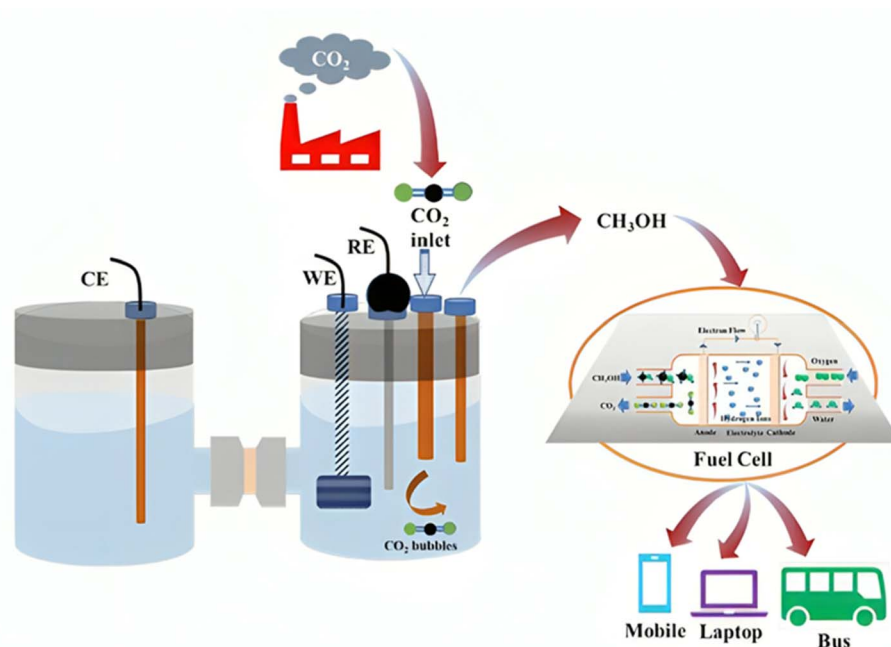
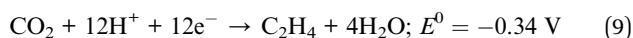
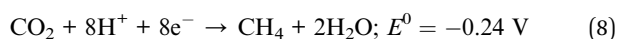
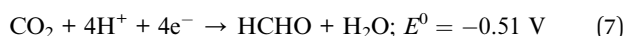


Fig. 4 Schematic representation of ECO_2R to CH_3OH .¹³⁸



Fig. 5 Reaction mechanism of the electrochemical CO_2RR on metal electrodes in aqueous solutions.²²⁴



From the above reaction sequences, it can be observed that the overpotential of CO_2 is high (eqn (4)) and it's a multi-electron process. The CO_2 reduction is challenging as it generates the hydrogen evolution reaction (HER) if we compare it with the last two reactions. Again, for the CO_2 reduction reaction, the following processes are involved in the cathode (reduction) and anode (oxidation):



reaction conditions and serve as stable intermediates during the production of CH_3OH .^{243,244} The methanol synthesis proceeds through the formate mechanistic pathway over Pd based catalysts Pd/ $\beta\text{-Ga}_2\text{O}_3$, Pd@Zn core shell catalyst, and Pd₄/In₂O₃.^{231,245,246}

In this mechanism, the C–O bond gets dissociated by the hydrogenation of $\text{HCOO}^*/\text{H}_2\text{COO}^*$ and is the rate determining step of the reaction.^{247–249} According to the microkinetic model, the rate determining step is the hydrogenation of HCOO to H_2COO on Pd– $\text{Ga}_2\text{O}_3/\text{silica}$.^{250,251}

4.2 The revised HCOO mechanism

According to studies on a revised formate pathway, HCOO^* is hydrogenated to form HCOOH^* , which is then hydrogenated to form H_2COOH^* and dissociates to form H_2CO^* and OH. H_2CO^* is then hydrogenated *via* intermediate CH_3O^* formation to form methanol.^{252,253} A similar *r*- HCOO mechanism was proposed by Behrens *et al.* The DFT calculation studies revealed that compared to $\text{PsCu}_3(111)$, the surface of PdCu (111) with an unsaturated Pd atom is more active for the adsorption and activation of CO_2 and H_2 .²⁵³

4.3 The RWGS + CO-hydro mechanism

In this mechanism, CO_2 is transformed to CO *via* a COOH^* intermediate, then CO is hydrogenated to produce methanol using intermediates HC, H_2CO , and H_3CO and CO is the byproduct.^{254–256} While HCO, H_2CO , and H_3CO intermediates directly contribute to the hydrogenation of methanol, CO can still be generated by dissociating CO_2 without an intermediate. This mechanism has been suggested for Au-based systems such as Au/ $\text{CeO}_x/\text{TiO}_2$.²⁵⁷

4.4 The *trans*-COOH mechanism

Hydrocarboxyl COOH^* is the first hydrogenated species in this molecular route. COOH is generated when CO_2 and the H atom of H_2O react.^{226,258–260} Methanol is formed when COOH^* is further hydrogenated to COHOH^* , which is then dissociated to COH^* *via* intermediates such as HCOH and H_2COH . This mechanism was proposed over the surface of Au/Cu–ZnO– Al_2O_3 and Ga_3Ni_5 .^{261,262}

One of the major challenges in methanol synthesis from CO_2 over heterogeneous catalysts is severe operating conditions including high pressure and temperature. Additionally, the thermodynamics and the continuous separation of methanol

from CO_2 and byproducts in the recirculating process constrain CO_2 thermocatalytic hydrogenation. Various methods for CO_2 reduction to methanol have been developed in recent years, including homogeneous catalysis, photocatalysis, and electrocatalysis. The benefits of the new technologies encompass lower temperatures compared to heterogeneous catalysis, the utilization of alternate energy sources (light or electricity), and the potential for enhanced methanol selectivity.

4.5 Electrocatalytic mechanism

Electrocatalysis is a process in which the catalyst plays a pivotal role by decreasing the activation energy of the reaction *i.e.* accelerating the reaction with faster electron transfer and it remains unchanged at the end. Typically, these electrocatalysts are heterogeneous catalysts as the reactions take place on the surface of the electrocatalyst. The process involves three major steps: (a) reactants adsorb onto the catalyst surface, (b) the chemical reaction takes place on the surface, and (c) the products desorb from the catalyst surface. To evaluate the catalytic activity of different electrode materials, researchers commonly compare the current density at a fixed overpotential or determine the overpotential required to achieve a specific current density. An efficient electrocatalyst demonstrates high current density at low overpotential, indicating both high activity and energy efficiency.²⁶³

Electrocatalytic processes generally occur in cathodes and anodes of fuel cells and also in electrolysis devices. In the anode, fuel gets oxidized and at the cathode, the oxygen reduction reaction occurs, producing electrical energy. In the anode, various fuels can be used for oxidation purposes, such as methane, ammonia, alcohols, hydrogen and sugars. For the cathode, another alternative can be H_2O_2 as an oxidant. A single atom catalyst (SAC) represents the ultimate small size limit of metal particles, which is generally used as a catalyst with the help of a support such as metal oxides, metal surfaces or graphene. The SAC contains isolated atoms singly dispersed on a support. With well-defined dispersion on the support surface, it exhibits maximum efficiency and selectivity. Furthermore, the most efficient way to maximize the utilization of every metal atom in supported metal catalysts is to reduce the metal nanostructures to well-defined, atomically dispersed active centers, known as single-atom catalysts (SACs) (Fig. 7). This represents the ultimate achievement in fine dispersion. For example, Zhang *et al.* developed a practical platinum single-



Fig. 7 Schematic diagrams illustrating different types of SACs. Reprinted with permission from ref. 264. Copyright permission from 2013 American Chemical Society.



atom catalyst supported on iron oxide designated as Pt₁/FeO_x.²⁶⁴ Moreover, the preparation of SACs is very challenging as single atoms tend to get agglomerated. The SACs can be applied in different electrochemical applications, such as the hydrogen evolution reaction (HER), oxygen evolution reaction (OER), oxygen reduction reaction (ORR), nitrogen reduction reaction, and carbon dioxide reaction. The mechanisms of these reactions are discussed in detail in ref. 265.

P. Sharma *et al.* reported a straightforward synthesis strategy for a single-atom ruthenium (Ru) catalyst integrated into a photoactive mesoporous C₃N₄ (mC₃N₄) support. Using the RuSA-mC₃N₄ catalyst under ambient conditions and visible light, efficient photocatalytic conversion of CO₂ into methanol was achieved. The process yielded an impressive 1500 μmol g⁻¹ of methanol within 6 hours, utilizing a low ruthenium loading of just 0.4 wt%.²⁶⁶ The image depicts the possible photocatalytic mechanism of the RuSA-mC₃N₄ catalyst under visible light irradiation during the conversion of CO₂ to methanol. They have narrowed the band gap compared to other prepared materials which helps to generate more electrons upon visible light irradiation. The incorporated Ru single atom on the C₃N₄ network traps electrons from C₃N₄ which helps to sustain the photogenerated electron-hole pair for a longer time. As a result, easy electron transfer occurs to reduce CO₂ which adsorbs on its surface and transforms into methanol (Fig. 8).

Here's an explanation of the process:

1. Photoexcitation (light absorption):

(a) When visible light is irradiated on the catalyst, the electrons present in the valence band of the mC₃N₄ photoactive support get excited.

(b) These excited electrons are promoted to the conduction band (CB), leaving behind holes (h⁺) in the VB of the same metal.

(c) In this particular case *i.e.* the RuSA-mC₃N₄ catalyst has a band gap (energy difference between the CB and VB) of approx. 2.50 eV, enabling the absorption of photons from visible light.

(2) Electron transfer and catalysis:

(a) After excitation of the electrons to the CB, the electrons are transferred to the Ru single atoms (Ru⁺) embedded in the mC₃N₄ matrix, also reducing the photocarrier transfer barrier. These Ru atoms act as active sites for catalytic reactions.

(b) The electrons reduce CO₂, leading to the formation of methanol (CH₃OH) and side products identified as CO and CH₄ gases.

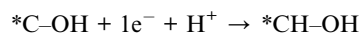
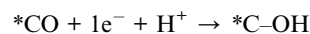
3. Hole utilization:

(a) The holes (h⁺) in the VB participate in the oxidation of water (H₂O), producing oxygen (O₂) and releasing additional protons (H⁺).

(b) This step regenerates protons necessary for the reduction process.

4. Reduction and oxidation reactions:

(a) On the CB side, the reduction reactions include: first, CO₂ gets adsorbed on the surface of the catalyst, reduced to a COOH* intermediate, and then further reduced to CO. Later CO transformed into methanol after 6 steps, as given below:²⁶⁵



(b) On the VB side, oxidation reactions occur:



5. The catalytic journey of the CO₂ hydrogenation reaction

The review provides a strategic action plan to address the negative impacts of CO₂ emissions on Earth's ecosystems. The strategy places an emphasis on reducing the use of fossil fuels and implementing catalytic technologies for CO₂ conversion. Specifically, it focuses on the mixed and electrocatalytic transformation of carbon dioxide to methanol using noble metals. It goes into great detail about thermodynamics, problems, and techniques used in CO₂ hydrogenation. We present a study of the historical development of catalysts and their industrial



Fig. 8 A plausible schematic illustration of the photocatalysis pathway under visible light irradiation. Reprinted with permission from ref. 266. Copyright permission from 2021 Wiley-VCH GmbH.



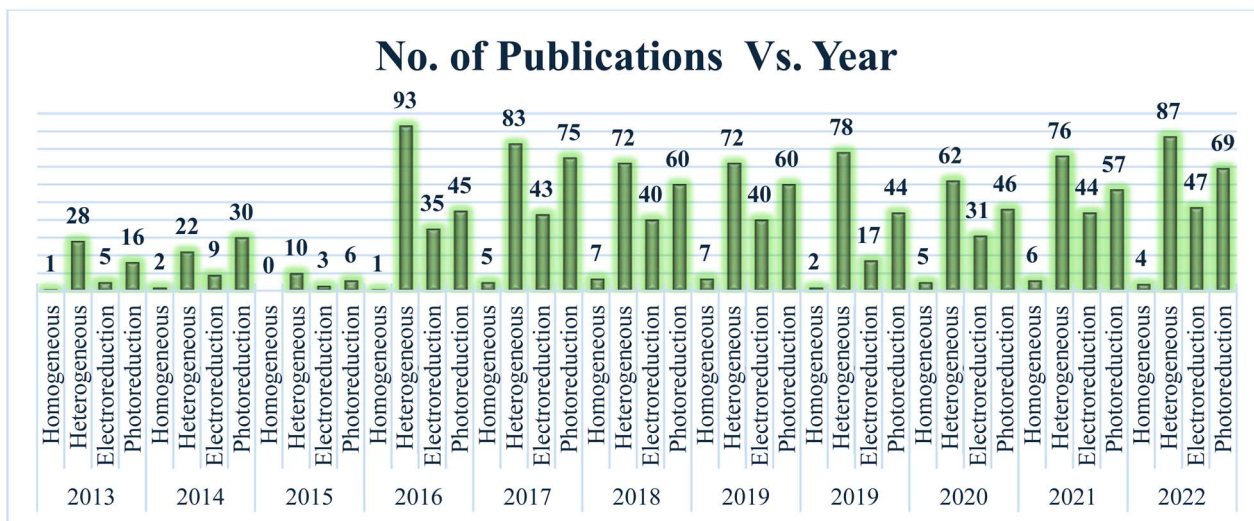


Fig. 9 The number of publications per year during the period of 2013 to 2022.

applications, emphasizing the novel approach towards achieving carbon neutrality. The transformation of carbon dioxide (CO₂) into methanol is a subject of ongoing research and development in the field of catalytic science (Fig. 9). Over time, the discovery of numerous catalysts and the increasing understanding of their behavior and effectiveness have led to significant progress towards a sustainable future. The recognition of the BASF-ZnO-Cr₂O₃ compound as a catalyst for the reduction of carbon dioxide to methanol in 1920 marked a significant achievement in this area.²⁶⁷ The discovery of ICI-Cu-ZnO-Al₂O₃ as an effective catalyst for the same process in 1960 significantly expanded the potential of this conversion.²⁶⁷ The discovery that Frost made in 1988 on the “Junction Effect Interaction” of catalysts opened up new doors for the creation of catalysts that were more effective.²⁶⁸ The Nobel Prize for the “Methanol Economy” in 1994 highlighted the importance of converting carbon dioxide into methanol as a means of promoting sustainability. The year 1994 further solidified this concept. Significant progress in the conversion of carbon dioxide to methanol was made possible by the development of catalysts that were supported on nanocrystals of copper in 2002. Subsequently, researchers conducted an investigation into the correlation between oxygen vacancies and reactive flaws in ceria surfaces, leading to the development of even more effective catalysts.²⁶⁹ The publication of the book “Beyond Oil and Gas: The Methanol Economy” in 2006 heightened awareness of methanol’s potential as an environmentally friendly alternative to fossil fuels.²⁷⁰

In 2011, the idea of an “Anthropogenic Chemical Carbon Cycle for a Sustainable Future” was presented, with the primary focus being placed on the necessity of converting carbon dioxide into methanol in order to reduce greenhouse gas emissions.⁸³ The creation of copper-ceria/copper-ceria-titania catalysts in 2014 was a significant step forward, as these catalysts demonstrated increased efficiency in the process of converting carbon dioxide to methanol.²⁷⁴ In 2017, active sites on

Cu/ZnO catalysts were investigated, yielding significant knowledge on the mechanism of CO₂ reduction to methanol.²⁷⁵ The catalyst support primarily scatters the active phase to prevent metal particles from sintering, while also ensuring thermal stability. Numerous experiments have demonstrated that the catalyst support influences the activity and selectivity of the methanol reaction. There are several types of carbon nanofibers (CNFs), including zirconia, silica, alumina, and carbon nanotubes (CNTs).^{276–285} In certain instances, a promoter may not yield the desired effect. Furthermore, it has the potential to influence the catalyst’s efficiency by either promoting the intended reaction or minimizing the incidence of undesirable reactions. As a result, incorporating promoters has the potential to improve both the product’s selectivity and the catalyst’s activity. There are several researchers who have documented the utilization of promoters for CH₃OH synthesis catalysts. Some examples of these promoters are gallium oxide (Ga₂O₃), zinc oxide (ZnO), niobium oxide (Nb₂O₅), and others.^{286–290} The year 2019 saw the discovery of ternary interactions in Cu-ZnO-ZrO₂ catalysts, which extended the possibilities for catalyst development that are even more effective.²⁹¹ The year 2020 saw the discovery of the one-of-a-kind interaction that occurs between copper and zinc in the Cu/ZnO system. This discovery opened up new possibilities for the creation of catalysts that are even more efficient.²⁹² The most recent breakthrough in this area is the creation of a new black indium oxide catalyst in 2022. This catalyst facilitates the effective conversion of carbon dioxide into methanol, which serves as a source of energy and a chemical feedstock, and represents a significant step towards a more sustainable future.²⁹³ The constant process of transforming carbon dioxide into methanol through the application of catalytic technology, defined by countless discoveries and breakthroughs, has been a journey. These achievements are critical milestones in developing a sustainable future and highlight the potential of catalytic science in making the world a better place (Fig. 10).





Fig. 10 Some remarkable journeys of hydrogenation of CO₂ to CH₃OH using heterogeneous catalysts.^{83,225,268–273}

5.1 Noble metal-based heterogeneous catalysts

In the mid-19th century, heterogeneous catalysts were utilized for the production of CH₃OH from syngas, employing a Cu–ZnO based heterogeneous catalyst in this exothermic process.^{294,295} The Cu–ZnO catalyst exhibited significant deactivation and diminished activity with standard syngas, which improved in the late 1990s, followed by the introduction of noble metal-based heterogeneous catalysts that enhanced the hydrogenation conversion of CO₂ to CH₃OH. Compared with transition metal-based catalysts, noble metal-based catalysts generally have higher activity in the CO₂ hydrogenation process. For successful CO₂ hydrogenation, both CO₂ and H₂ should be activated simultaneously, and the noble metal nanoparticles are usually more active for H₂ activation with the enhanced hydrogen spillover phenomenon than transition metal nanoparticles, hence noble metal-based catalysts usually outperform transition metal-based catalysts in CO₂ hydrogenation. Furthermore, noble metal nanoparticles are more enduring than transition metal nanoparticles in terms of coke formation, which allows noble metal-based catalysts to have a longer catalytic lifetime. The details about the noble metal-based heterogeneous catalysts for CO₂ to methanol conversion are discussed as follows.

5.1.1 Pd based catalysts. CH₃OH production from CO₂ is catalyzed using two main catalytic systems: Cu and Pd catalysts, which have good catalytic activity and selectivity.^{155,242,296–299} One of the main difficulties in producing methanol from CO₂ is catalyst deactivation.^{300–302} Pd serves as a promoter for the Cu–ZnO catalyst in the hydrogenation of syn-gas to methanol.^{303,304} The electronic state of the catalyst affects the interaction between Pd and Cu, with Pd promoting hydrogen spillover and enhancing the stability of the Cu active site against CO₂ oxidation.^{305,306} The alloy phase diagram has shown that Pd-based metal alloy catalysts such as Pd–Zn, Pd–Cu, Pd–Ga, and Pd–In

alloys can be employed for CO₂ hydrogenation.^{307–313} The new active site with high activity is created by changing the chemical properties of the metal surface by employing alloys and ultimately increasing the catalytic activity. The alloy composition depends on the metal composition and reduction conditions to tune the atomic ratio of the two components. Different Pd supported catalysts, including mesoporous MCM-41, SBA-15, and carbon based materials such as CNFs, CNTs, *etc.*, increased catalytic activities and led to the development of various synthetic routes, including CVI (chemical vapour impregnation), citrate decomposition, incipient wetness impregnation, atomic layer deposition *etc.*^{314–317} These methods are crucial for CH₃OH synthesis activity and the development of highly active catalysts at low temperatures.

5.1.2 Pd–ZnO based catalysts. The Pd–Zn alloy is one of the notable bimetallic catalysts employed for the synthesis of CH₃OH. In 2004, Iwasa *et al.* reported a Pd/ZnO catalyst for CH₃OH synthesis from CO₂.³¹⁸ The catalytic performance of Pd/ZnO/Al₂O₃ was investigated by Geng and coworkers.³¹⁹ Pd–Zn alloys can influence the deactivation of the catalyst for methanol synthesis and stabilize formate intermediates during CH₃OH synthesis, as reported by Bahruji and coworkers. The particle size and oxidation state have a significant impact on the catalytic performance of Pd, as shown by Bahruji and coworkers.^{320,321} Liao and co-workers developed the low-pressure methanol synthesis method by utilizing a Zn enriched Pd–Zn core–shell catalyst from sodium selenite, cadmium nitrate, and 5% Pd with ZnO supported (Pd/CdSe–ZnO) precursors. The uniqueness of this catalyst is that it suppresses the CO production by the RWGS reaction.³²² Zaman and co-workers were the first to report Ca doped Pd–Zn on the CeO₂ catalyst for methanol synthesis from CO₂ hydrogenation. It was observed that CeO₂-supported PdZn showed high





Fig. 11 Electron microscopy and spectroscopy of spent catalyst 0.5Ca5P5ZZr-IMP. SEM image (a) and corresponding energy dispersive spectrum (EDS) (b) of 0.5Ca5P5ZZr-IMP, SEM image (c) and EDS (d) of 5P5ZZr-IMP. Surface mapping (e) and PdZn distribution (f) in 5P5ZZr-IMP.³²³ Copyright 2019 Elsevier.

selectivity in catalytic activity and Ca-doped PdZn/CeO₂ showed 100% methanol selectivity at low temperatures³²³ (Fig. 11). Diez-Ramirez and coworkers reported a carbon nanofiber-based PdZn catalyst for methanol synthesis from CO₂ at atmospheric pressure, with the performance of the catalyst dependent on the particle size.³²⁴ In recent years, Yerga *et al.* synthesized PdZn–ZnO catalysts on TiO₂ with Zn/Pd molar ratios of 2.5, 5, and 7.5 using metal organic precursors. The experimental studies reveal that the catalyst with the highest ZnO content achieved the best methanol yield (78.9 mmol_{MeOH} min⁻¹ mol_{Pd}⁻¹) due to enhanced CO₂ adsorption, greater ZnO particle stability, and intermediate hydrogenation.³²⁵ Tian and coworkers synthesized a Pd/ZnO single atom

catalyst for methanol steam reforming. The experimental studies showed that the TOF of 2PdZn/Al₂O₃ NP is 1.4 times that of 0.2PdZn SAC.³²⁶

5.1.3 Pd–Cu based catalysts. There has been a surge in research utilizing bimetallic Pd–Cu catalysts for the synthesis of methanol from CO₂. Jiang *et al.* examined the utilization of SiO₂-supported Pd–Cu catalysts in the process and determined that the partial pressure has a significant impact on CO₂ hydrogenation. The use of bimetallic catalysts was found to enhance the activity and reduce the selectivity of methanol. A kinetic study showed that the synthesis of CH₃OH was dependent on the H₂/CO₂ ratio and that the Pd–Cu bimetallic catalyst played an active role.³²⁷



This group reported another study that elaborated on the connection between the size effect, surface alloy composition and catalytic efficiency. This work mainly focused on the manufacture of a Pd–Cu bimetallic catalyst; the ratio of Pd/(Pd + Cu) lies within 0.25–0.34 and is used for the hydrogenation of CO₂ to produce CH₃OH. The main observation is that Pd–Cu(2.4)/SiO₂, which has a lower metal loading than a commercial catalyst, produces 2 times as much CH₃OH at 523 K and 4.1 MPa concerning metal-based space-time yield (STY).³²⁸ Lin *et al.* conducted an investigation into the use of various supports, including TiO₂, ZrO₃, CeO₃, Al₂O₃, and SiO₂, for the Pd–Cu catalyst. The results indicated that TiO₂ and ZrO₂ showed the highest activity for methanol synthesis. The adsorption capacity for methanol synthesis is attributed to the influence of metal support interaction on the process, with the Pd–Cu catalysts facilitating the bonding between H₂ and CO₂ on the surface.³²⁹ The changes in metal–support interactions were primarily attributed to enhancing moderate interactions between the metal and support, which aimed to boost adsorption capacity and promote methanol synthesis. This study supported the idea that Pd–Cu catalysts play a significant role in shifting adsorption toward bonding between H₂ and CO₂ on the alloy surface.

5.1.4 Pd–Ga catalysts. Several research studies have been conducted to explore the use of Pd–Ga₂O₃ catalysts for methanol synthesis from CO₂. Fujitani *et al.* reported that the Pd–Ga₂O₃ catalyst showed higher catalytic activity compared to the commonly used Cu/ZnO catalyst.³³⁰ In 2002 Collins *et al.* reported that dissociated atomic hydrogen spillover from metallic Pd to Ga₂O₃ causes Pd NPs to accelerate the hydrogenation rate of carbonaceous species chemisorbed over the surface of b-Ga₂O.³³¹ Behrens *et al.* synthesized a series of Pd–Ga catalysts consisting of intermetallic compounds, and found that gamma Ga₂O₃ played a significant role in the selective hydrogenation of

methanol.³³² Damsgaard and co-workers synthesized a non-dispersed intermetallic GaPd₂/SiO₂ catalyst for the synthesis of methanol from CO₂. This intermetallic catalyst showed higher catalytic activity than Cu/Zn/Al₂O₃ which was the most used catalyst. *Ex situ* and *in situ* characterization techniques, reveal that different aspects of the catalytic structure show a good correlation between the results at various pressures. The TEM study introduced a deeper evaluation of the dynamic catalytic activity during methanol synthesis at atmospheric pressure.³³³ Tsang and co-workers reported that the interaction of Pd and Ga₂O₃ nanocrystals with a predominant 002 surface on metal supports resulted in enhanced catalytic activity for the synthesis of methanol from CO₂ hydrogenation. This work emphasizes electron transfer from Ga₂O₃ to Pd NPs (nano particles) thereby enhancing the reduction process of Ga³⁺ and directly enriching the conversion process from CO₂ to methanol.³³⁴ Williams and co-workers synthesized a colloidal Pd₂Ga-based catalyst by thermal decomposition of Pd(II) acetate in the presence of the Ga(III) state. Various characterization techniques, such as HR-TEM, STEM, XPS, and XRD support the formation of Pd₂Ga nanoparticles with an average diameter of 5–6 nm. This work is considered the benchmark of methanol synthesis and the Pd/Ga colloidal catalyst shows promising stability and higher catalytic activity than the Cu–ZnO–Al₂O₃ catalyst for the conversion of CO₂ to methanol.³³⁵ Michael Bowker and his colleagues conducted another intriguing study. This study examines the Pd deposition on Ga₂O₃ and In₂O₃ for CO₂ hydrogenation to methanol. The interesting finding in this work is that Ga₂O₃ is active alone, but In₂O₃ achieves high conversion and 89% methanol selectivity.³³⁶

Morgan and coworkers³³⁶ synthesized a nanodispersed intermetallic GaPd₂/SiO₂ catalyst; industrially relevant high-surface-area SiO₂ is impregnated with Pd and Ga nitrates, then dried, calcined, and reduced in hydrogen (Fig. 12). The



Fig. 12 (a) XRD patterns obtained from the impregnated, dried, and calcined catalyst precursor at room temperature and atmospheric pressure, and (b) from the reduced and tested GaPd₂/SiO₂ catalyst for CO₂ hydrogenation. Reprinted with permission from ref. 333. Copyright 2015 American Chemical Society.





Fig. 13 IL-TEM images of the GaPd₂/SiO₂ catalyst acquired after drying (a), calcination (b), reduction (c), and methanol synthesis (d).³³³ Copyright 2015 American Chemical Society.

GaPd₂/SiO₂ catalyst outperforms the traditional Cu/ZnO/Al₂O₃ catalyst for CO₂ hydrogenation to methanol at ambient pressure. Additionally, it produces less unwanted CO. The GaPd₂/SiO₂ catalyst is investigated using both *in situ* and *ex situ* approaches (Fig. 13).

5.1.5 Pd–In based catalysts. Pd–In-based catalysts have emerged as a promising option for the production of methanol from CO₂ due to the presence of oxygen vacancies, which allow for the adsorption of carbon dioxide. The catalytic activity of these catalysts can be improved through catalytic activation. García-Trento *et al.* proposed a bimetallic PdIn nanoparticle synthesized by the thermal decomposition of Pd(acetate)₂ and In(acac)₃. This Pd/In (5–10 nm) nanoparticle catalyst showed improved > 80% methanol selectivity at 270 °C compared to the reference Cu/ZnO/Al₂O₃ catalyst.³³⁷ Snider *et al.* synthesized Pd–In-based catalysts with different In/Pd ratios (1 : 0, 2 : 1, 1 : 1, 1 : 2, and 0 : 1) and enhanced the methanol synthesis process from CO₂/H₂ at 40 bar and 300 °C. The highest methanol selectivity of 61% was achieved using the In : Pd (2 : 1)/SiO₂ catalyst. *In situ* XAS characterization technique revealed that the synergistic effect of the intermetallic compound indium–palladium enhances the selectivity and activity of methanol synthesis.³³⁸

Liu *et al.* synthesized Pd/In₂O₃ catalysts by thermal treatment of In₂O₃ powder with a Pd/peptide composite. The Pd/In₂O₃ catalyst showed higher activity of methanol synthesis from CO₂ conversion *i.e.* >20% and methanol selectivity of 70%.³³⁹ Jeschke and coworkers developed the catalyst Pd–In₂O₃–ZrO₂ by flame spray pyrolysis methods for the conversion of CO₂ to methanol. Its high and persistent methanol productivity can be explained by the improved formation of oxygen vacancies revealed by this particular catalyst architecture, according to a ground-breaking procedure designed to quantify them using *in situ* electron paramagnetic resonance spectroscopy.³⁴⁰ Recently, Cai *et al.* have reported that hollow In₂O₃ supported Pd based catalysts are suitable for CO₂ hydrogenation to methanol. The main finding of this work is that the hollow morphology of In₂O₃ supported Pd based catalysts led to higher catalytic performance (10.5% CO₂ conversion, a methanol selectivity of 72.4% and a methanol space time of 0.53 g_{MeOH} h⁻¹ g_{cat}⁻¹ over 100 h on stream at 3 MPa and 295 °C) compared to In₂O₃ nanotube or nanorod morphology.³⁴¹ Jiang and coworkers reported the use of an In₂O₃/SBA-15-supported Pd-based catalyst and observed a CO₂ conversion rate of 12.6% with 83.9% methanol selectivity.³⁴² Hua and coworkers developed the Pd/In₂O₃



nanocatalyst by employing innovative electrostatic self-assembly methods. This catalyst exhibited an increase in the concentration of oxygen vacancies which enhanced the methanol production. This catalyst led to a space time yield (STY) of $0.54 \text{ g}_{\text{MeOH}} \text{ h}^{-1} \text{ g}_{\text{cat}}^{-1}$ (300 °C, 3.5 MPa, 21 000 mL $\text{g}_{\text{cat}}^{-1} \text{ h}^{-1}$).³⁴³

5.1.6 Mesoporous molecular sieves supported Pd-based catalysts. Song and co-workers reported a nanostructured Pd-based catalyst by the incorporation of mesoporous MCM-41 and SBA-15 and created a nano-sized pore channel using alkali/alkaline earth metal additives, where they observed the addition of an alkali/alkaline earth metal as a promoter enhanced the catalytic activity of methanol synthesis from CO_2 .^{344–346}

The CNT-supported Pd-based catalyst shows high catalytic activity for methanol synthesis. Zhang and coworkers synthesized Pd–ZnO supported multi-walled carbon nanotube-based catalysts showing a high rate of catalytic conversion of methanol from CO_2 . A large amount of hydrogen is reversibly adsorbed using CNT-supported Pd–ZnO catalysts, which boosts the concentration of active H-species at the surface of the working catalyst and accelerates the kinetics of the hydrogenation reaction.³⁴⁷ Kong and co-workers developed a MWCNT supported Pd–Ga catalyst for the synthesis of methanol by hydrogenation. This catalyst improved the molar percentage of catalytic activity of Pd^0 species and also increased the catalytic activity of adsorbing/activating H_2 .³⁴⁸ Li *et al.* investigated the Pd nanoparticle supported inside and outside CNT-based catalysts. Higher catalytic activity and methanol selectivity are displayed inside the Pd/CNTs than outside. The turnover frequency of Pd/CNTs (inside) is 3.7 times higher than that of outside-supported CNTs. The selectivity difference between inside and outside CNT-based catalysts is due to the relative concentration of Pd^+ species.³⁴⁹

Pd metal actively influences the chemical and electronic properties of the catalyst surface. Furthermore, it is impossible to overstate the importance of Pd's role in converting H_2 into H-add species and permitting them to overflow onto support surfaces because this is still an essential step in the synthesis of methanol, without which hydrogenation cannot proceed properly. The Pd precursor employed for the synthesis of the catalyst will also affect its overall performance.

5.1.7 Effect of Pd as a promoter. In chemistry, catalyst promoters play an important role by improving the catalytic activity and selectivity. In this section, we have discussed the role of Pd as a promoter and its direct influence on the physicochemical properties of the CO_2 hydrogenation reaction and enhancing the surface area and mechanical strength of the catalyst.

The promoters on a Pd surface enhance the CO_2 adsorption capacity by generating an electrostatic field. Cabrera *et al.* observed that Pd itself acts as a promoter which increases the catalytic activity of Cu + ZnO (Al_2O_3) and improves the rate of hydrogenation of CO_2 due to the hydrogen dissociated on the surface of Pd particles and spillover on the surface of the Cu + ZnO catalyst. In another remarkable study established by Lee and co-workers, the catalytic activity of Cu/CeO₂ was increased by the addition of a small amount of Pd. A small amount of Pd is

added to the Cu/CeO₂ catalyst to facilitate the reactivity of Cu sites, which in turn increases methanol productivity. The interaction with highly dispersed Pd increases the surface and dispersion concentration of Cu. The transfer of electrons from palladium to copper leads to a reduction in copper sites, while the addition of palladium as a promoter diminishes the surface area of cerium dioxide. So, it can be concluded that the rate of hydrogenation of CO_2 and methanol productivity can be increased with the addition of a small amount of Pd to the Ce/CeO₂ catalyst.³⁵⁰ Hu *et al.* reported Pd promoted Cu–ZnO catalysts for the synthesis of a series of Pd doped Cu–ZnO catalysts with a constant Cu/Zn ratio (1 : 1) and varied Pd molar ratios from 0.01 to 0.04 mol%. It was observed that the 1% Pd doped Cu–ZnO catalyst promotes the methanol space-time yield by 2.5 times and turnover frequency (TOF) by 3.5 times at 543 K as compared to the undoped Cu–ZnO catalyst. Tsang *et al.* investigated the effect of the promoter Pd on the Pd/ZnO/ Al_2O_3 catalyst. The result indicated that methanol selectivity depends on the ratio of Pd^0/PdZn and the EXAFS study showed that the Pd-modified ZnOx possesses an active site for methanol synthesis.³⁰⁵ Koizumi *et al.* investigated the incorporation of Pd nanoparticles into mesoporous supports such as MCM-41, and SBA-15 with promotion using alkali/alkaline earth metals synthesized by incipient wetness impregnation. It was observed that without impregnation of any promoters, Pd-supported mesoporous silica showed weak activities towards methanol synthesis, but the addition of alkali or alkaline earth metals such as K, Mg, and Ca increased the catalytic activities of K(Ca) promoted Pd-supported mesoporous SBA-15 producing two times higher methanol yield than that of Pd-supported mesoporous silica. Song and co-workers synthesized Pd supported catalysts by the impregnation method with $\text{Pd}(\text{NO}_3)_2$. CaO promoted the CO_2 hydrogenation activity with the highest selectivity for methanol over Pd/MCM-41.³⁴⁴ Yin and co-workers reported a metal–organic framework-based PdZnO catalyst from the Pd@zeolitic imidazolate framework (ZIF-8) for hydrogenation of CO_2 . The formation of small-sized PdZn alloy particles after H_2 reduction and the abundance of surface oxygen defects on ZnO are crucial for such a high methanol production. The SMSI between PdZn and ZnO also ensures the long-term stability of the PdZn catalysts. Lastly, it can be proposed that the active site strongly associated with methanol formation is the PdZn alloy rather than metallic Pd.³⁵¹

(i) Au based catalysts

Researchers have discovered that gold nanoparticles act as highly active catalysts for CO_2 hydrogenation. Vourros *et al.* successfully investigated the activity of Au nanoparticles supported on various oxides (M_xO_y – Al_2O_3 , TiO_2 , Fe_2O_3 , CeO_2 , and ZnO) to catalyze the synthesis of methanol from the hydrogenation of CO_2 . Au nanoparticles based on Au/CeO₂ (82%) and Au/ZnO (90%) show high selectivity towards CH_3OH synthesis at temperature below 250 °C.³⁵² Behm and co-workers synthesized metal oxide-supported Au catalysts (Au/ Al_2O_3 , Au/ TiO_2 /Au/ZnO, and Au/ZrO₂) for the synthesis of 'green methanol' from CO_2 . The Au/ZnO catalyst is one of the potential candidates for green methanol technology. With an increase in the diameter of Au nanoparticles in the Au/ZnO catalyst, the rate of methanol



Table 1 The summary of noble-metal based catalysts for the hydrogenation of CO₂ to methanol

Catalyst	CO ₂ /H ₂ ratio	Temp./K	MPa	Space velocity	Conv.	Selectivity	STY	Ref.
Pd/ZnO	1:3	523 K	2	3600(W)	10.7	60	77.4	320
PdZn-400	1:3	543 K	4.5	21 600(W)	15.1	56.2	650	365
Pd/Ga ₂ O ₃	1:3	523 K	5	—	19.6	51.5	<i>c.a.</i> 20.8	334
Pd–In ₂ O ₃ (Co-precipitation)	1:4	553 K	5	24 000	—	75	0.061	366
Pd(0.25–Cu/SiO ₂)	1:3	250 °C	41	3600	6.7	30	0.03	367
Pd/SiO ₂	1:3	523 K	2	—	0.33	31.6	0.013	349
Pd/Cu–P25	1:3	523 K	4.1	—	16.4	25.7	1.80	368
Pd/In ₂ O ₃	1:4	300 °C	50	21 000	20	72	0.89	369
Pd–Pt/In ₂ O ₃	1:4	300 °C	5	21 000	17.7	68.3	0.725	370
PdZn/ZnO-3.93Al	1:3	523 K	3.0	—	14.2	51.6	<i>c.a.</i> 4.51	371
Pd/Zn SiO ₂	1:3	260 °C	3	—	2.6	11.2	0.03	372
2Pd/CeO ₂ –R	1:3	240	3	2000	6.2	29	0.012	373
5% Pd/ZnO, IM	1:3	523 K	2.0	—	8.7	1	0.055	320
0.5Ca ₅ Pd ₅ ZnZr	1:3	523 K	3.0	2400	14.2	51.6	<i>c.a.</i> 4.51	374
Pd–Cu/SBA-15	1:3	250 °C	4.1	3600(W)	6.5	23	23	375
Pd/Zn/CNTs	1:3	250 °C	3	1800(W)	6.3	99.6	37.1	376
Pd Cu/CeO ₂	1:3	523 K	4.1	—	9.9	28.4	1.37	368
Pd/TiO ₂	1:3	523 K	5	—	15.5	3.9	<i>c.a.</i> 1.21	377
Pd–P/In ₂ O ₃	1:4	498 K	5	—	Ca 3	Ca 95	6.01	339
Pd/In ₂ O ₃ /SBA-15	1:4	533 K	5	—	12.6	83.9	11	314
Pd–ZnZrO _x	1:4	320 °C	5	24 000	16	58	0.63	378
Pt/In ₂ O ₃	1:4	300 °C	5	21 000	17.6	54	0.542	379
Pt/In ₂ O ₃	1:3	300 °C	4	24 000	8.8	71.5	0.480	380
Rh/In ₂ O ₃ –ZrO ₂	1:4	300	5	21 000	18.1	66.5	0.684	381
UiO-67-Pt	—	170	0.8	6000	1.5	19.0	0.0024	382
Au/ZnO	1:3	240 °C	0.5	4800(G)	0.3	82	N/A	383
Ag/ZrO ₂	1:3	240	80	3600	—	55	—	359
Ag/In ₂ O ₃	1:4	300 °C	5	21 000	13.6	58.2	0.450	384
Au/In ₂ O ₃ –ZrO ₂	1:3	250	50	21 000(G)	5.0	90	0.59	385
Au/Al ₂ O ₃	1:3	220	5	24 000(W)	2.0	3.8	—	383
Au/CeO ₂	1:3	240	5	9000	1–2	40	0.412	386
Au/In ₂ O ₃	1:4	300	5	21 000	11.7	67.8	0.47	387

formation reduces and the selectivity of methanol increases from 56% to approximately 82%.³⁵³ This group also reported better catalytic behaviour of the Au/ZnO-based catalyst for the synthesis of methanol than the conventional Cu–Zn–Al catalyst. From the kinetic and IR spectrophotometer studies, it is revealed that the conversion of CO₂ to methanol proceeds through the formation of formate and methoxy intermediates initiated using the proposed Au/ZnO catalyst.³⁵⁴ Han *et al.* reported an Au-supported ZrO₂ catalyst for methanol synthesis with a selectivity rate of 73% at 180 °C.³⁵⁵ The electrical polarization at the metal oxide CeO_x/TiO₂ anchored with Au nanoparticle-based substrates, as proposed by Chen *et al.*, actively promoted CO₂ adsorption under low pressure conditions and led to greater selectivity of methanol production. According to the AP-XPS study, Au possesses a partial negative charge and CeO_x shows a Ce³⁺ state. The DFT calculation studies supported the substantial charge redistribution occurring at Au₃/CeO_x/TiO₂(110), with Au atoms becoming negatively charged, and negatively charged Au and the positively charged Ce³⁺ site bind to the positively charged C atom and the negatively charged O atom of CO₂, respectively.³⁵⁶ Rodriguez and coworkers investigated the catalytic properties of In/Au(111) alloys and InO_x/Au(111) inverse systems for CO₂ hydrogenation by employing AP-XPS studies and batch reactors. The experimental evidence shows that InO_x/Au(111) demonstrates

significant potential for CO₂ hydrogenation combining high activity and selectivity for methanol production.³⁵⁷

(ii) Ag-based catalysts

Ag-based catalysts received less attention than Pd and Au-supported catalysts for the hydrogenation of CO₂.³⁵⁸ Grabowski *et al.* investigated the catalytic activity of Ag/ZrO₂ and Ag/ZrO₂/ZnO catalysts. The XPS and Auger spectroscopic techniques confirmed the electronic state of silver and the contents of the zirconia polymorphic phases (tetragonal and monoclinic). The presence of oxygen vacancies in ZrO₂ directly influenced the thermodynamically unstable t-ZrO₂ and Ag⁺ species connected with oxygen vacancies thereby accelerating the active phase for methanol synthesis.³⁵⁹

(iii) Pt/Rh based catalysts

In heterogeneous reactions, dispersed catalysts have a remarkable place due to the low coordination environment of the metal center, quantum size, and SMSI effect.³⁶⁰ Zheng *et al.* prepared atomically dispersed Pt/MoS₂ catalysts with Pt amounts up to 7.5% and reported that the synergetic interaction between neighboring Pt monomers reduces the activation energy and enhances the catalytic activity relative to isolated Pt monomers in CO₂ hydrogenation. Unlike isolated Pt monomers, neighboring Pt monomers hydrogenate CO₂ sequentially into formic acid and methanol.³⁶¹ Song *et al.* investigated a PtCo alloy-based catalyst for methanol synthesis where zigzag Pt–Co





Fig. 14 Electrochemical characterization studies of Pd/SnO₂ NSs (Pd : Sn = 1 : 1) in comparison with Pd NSs and SnO₂ NPs. (a) LSV curves obtained in 0.1 M NaHCO₃ solution. (b) FE for CH₃OH at various applied potentials. (c) Charging current density differences plotted against scan rates. (d) Chronoamperometry studies of different catalysts. Reprinted with permission from ref. 390. Copyright permission from 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

nanowires with a Pt-rich surface and abundant step/edges (defects) were utilized to obtain high catalytic activity. Pt₄Co NWs/C showed the best performance among other PtCo alloys.³⁰³ Analysis using Fourier transform infrared spectroscopy demonstrated that when Pt₄Co NWs/C was used as a catalyst, the process involved CO₂ adsorption and activation *via* a carboxylate intermediate, resulting in enhanced CH₃OH yield. Shimizu *et al.* investigated a Pt nanoparticle loaded MoO_x/TiO₂ catalyst for the hydrogenation of CO₂ to produce CH₃OH in 73% yield under mild conditions. The X-ray absorption fine structure study suggested that reducing the MoO_x species promoted the hydrogenation reaction.³⁶² Han *et al.* investigated that the methanol selectivity of In₂O₃ increased (72.2% to 91.1%) by introducing a small amount of Pt.³⁶³ Zeng and co-workers reported that the RhW alloy with a nanosheet structure acts as a catalyst for the synthesis of methanol by hydrogenation of CO₂. The 1D quantum confinement effect leads to a larger

d band level in the RhW alloy-based nanosheet, while an electronic effect associated with the alloy mechanism results in a negatively charged Rh surface (Table 1).³⁶⁴

Electrochemical catalytic conversion of CO₂ to methanol using precious metal catalysts is another interesting approach to CO₂ reduction that can be made through the electrochemical pathway. In this regard, several electrocatalysts such as CuAu, CuPd, and AgZn were found to be excellent candidates for enhancing the CO, CH₄, and CH₃OH productions, respectively. In addition, palladium-based electrocatalysts have not received much attention despite Pd's exceptional ability to show low overpotentials for the electrochemical reduction of CO₂. In this case, when Pd is supported on carbon (Pd/C), the C added to metals improves their different properties by making them more active because carbon materials are porous. Additionally, we can use C materials with a high surface area and good electrical conductivity to stabilize high metal loadings and



enhance the electron transfer rate in both directions (from and to) of metal catalyst sites.

Similarly, Pd/C started producing formate at 0.00 V vs. RHE, with hydrogen being the only by-product (0.00 to -0.20 V vs. RHE).³⁸⁸ So, the unwanted hydrogen evolution happens at the same time at Pd (supported on C) electrodes, along with the electrocatalytic reduction and hydrogenation of CO₂ to formate. However, the combination of Pd with Zn led to the formation of formate species that remain adsorbed on the PdZn alloy surface for long enough to be converted into CH₃OH. Another interesting study on Pd-based materials was reported by Han *et al.* Herein, the Pd combined with SnO₂, forming plentiful Pd–O–Sn

interfaces, undergoes four-electron transfer mechanisms for selective CO₂ reduction to methanol.³⁸⁹ This excellent design helped to achieve a faradaic efficiency (FE) of $54.8\% \pm 2\%$ for CH₃OH at -0.24 V vs. RHE, and was able to deliver higher energy density as compared to sole Pd nanosheets (NSs) and SnO₂ nanoparticles. They also reported that the current densities of Pd/SnO₂ NSs didn't change much, and a high FE of 54% retains over 24 hours, indicating that it is more stable. This structure not only facilitated CO₂ adsorption on the SnO₂ surface, but also made it difficult for CO to remain on Pd due to the Pd–O–Sn interface weakening the binding strength of CO to Pd. In turn, enhancing Pd catalysts' CO₂RR performance is



Fig. 15 (A) SEM, (B) and (C) TEM, (D) HR-TEM, and (E)–(G) EDX mapping images (scale bar: 20 nm). (H) Distribution of Pd (a) and Cu (b) in Pd₈₃Cu₁₇ by line-scan analysis. (I) SAED pattern of the Pd₈₃Cu₁₇ and pure Pd (scale bar: 10 1 nm^{−1}). (K) XRD pattern of the Pd₈₃Cu₁₇ aerogel. Reprinted with permission from ref. 389 Copyright permission from 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.



crucial in such a circumstance. Different types of electrochemical studies performed are given in Fig. 14.

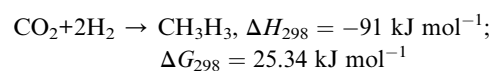
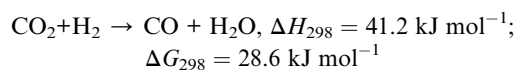
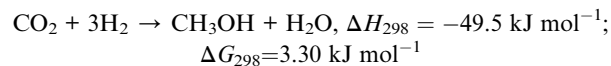
Another excellent study was carried out by Buxing Han *et al.*;³⁸⁹ they developed a Pd_xCu_y aerogel electrocatalyst and investigated it in a CO₂-saturated aqueous ionic liquid, 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim]BF₄) electrolyte containing 25 mol% [Bmim]BF₄ and 75 mol% water *via* a H-type cell. The characterization studies of that sample were carried out by SEM, TEM, HRTEM, SAED and XRD and the results are given in Fig. 15.

They achieved the highest Brunauer–Emmett–Teller (BET) surface area of 76.9 m² g⁻¹ for Pd₆₇Cu₃₃ aerogels. This aerogel was capable of delivering FE efficiency for CH₃OH within the range of -1.9 V to -2.4 V (*vs.* Ag/Ag⁺). It has been found that the proportion of Cu present in the aerogel also played a crucial role in the FE of CH₃OH. In a [Bmim]BF₄ aqueous solution with 25 mol% [Bmim]BF₄ and 75 mol% water, the FE for CH₃OH production for Pd₈₃Cu₁₇ is highest (80.0%) among others at -2.1 V (*vs.* Ag/Ag⁺) after 5 hours of electrolysis. For this material, the results of the electrochemical characterization studies are given in Fig. 16.

Unlike Pd, the intermediate cannot be stabilized long enough for the reverse water-gas shift (RWGS) reaction to proceed without the intermediate first being decomposed to give CO and H₂O.³²⁰



Here, we need to discuss the RWGS process. In general, an exothermic reaction occurs during the generation of methanol from carbon dioxide using a catalytic hydrogenation process. Numerous pilot plants have used this technical method, which combines the normal methanol synthesis process with the RWGS process.



The water formation at the 2nd step inhibits the methanol synthesis through a catalytic way. Hence, the design of materials is important in which the metal's tolerance towards the water is essential. Brisard *et al.*, using differential electrochemical mass spectrometry, studied the electroreduction of carbon dioxide at a Pt porous electrode.³⁹¹ With their findings, it was demonstrated that a Pt electrodeposited electrode could be



Fig. 16 The as performed CO₂ electroreduction reactions in ionic liquid [Bmim]BF₄ aqueous solution combined with 25 mol% [Bmim]BF₄ and 75 mol% water. (A) Different LSV curves for Pd_xCu_y aerogels are given such as: (a) Pd₆₇Cu₃₃, (b) Pd₇₁Cu₂₉, (c) Pd₈₃Cu₁₇, (d) Pd₈₇Cu₁₃, and (e) Pd₈₉Cu₁₁. (B) The FE for CH₃OH over Pd_xCu_y aerogels. (C) Current density and FE over Pd₈₃Cu₁₇ aerogel electrodes at @2.1 V vs. Ag/Ag⁺. (D) Tafel plots for CH₃OH production over Pd₈₃Cu₁₇ aerogel electrodes. Reprinted with permission from ref. 389. Copyright permission from 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.



used to produce CH_3OH in the presence of acidic media. These findings further indicated that CO was formed as an intermediate leading to the production of CH_3OH . As part of efforts to develop a reversible fuel cell based on CH_3OH , Shironita *et al.* recently studied the electroreduction of CO_2 on the carbon-supported Pt (Pt/C) and Pt–Ru (Pt–Ru/C) electrodes through a single cell. Faradaic efficiency estimates for the electroreduction of CO_2 range from 30–50%. They concluded that the reduction current decreases over time because of the accumulation of CH_3OH on the reaction active sites of the electrocatalyst (Pt/C). This is the reason the efficiency of yielding CH_3OH went from 0.03% at Pt/C compared to 7.5% in the case of Pt–Ru/C. Also, cyclic voltammetry measurements showed that the faradaic efficiencies of Pt/C and Pt–Ru/C were 35% and 75%, respectively. In addition to having a significant impact on the selectivity, reduction mechanisms, and efficiency of the CO_2 electroreduction process, the metal surface was also affected by a variety of other factors. In fact, it has been discovered that changing supporting electrolytes and operating circumstances has a significant impact on current density, product selectivity, and energy efficiency in CO_2 reduction even for the same metal electrode with the same purity.³⁹²

The binding energy of the reaction intermediates on the catalyst surface affects both the catalyst's reaction activity and selectivity. During the electrochemical reduction of CO_2 , a complex reaction occurs that involves multi-electron transfers and a diverse array of intermediates and products, hence it is necessary to regulate the adsorption energy of the various intermediate species that are produced. In order to modify the binding energy of intermediates for desired end products, it is rational to create specialized surface structures.

6. Challenges and possibilities of CO_2 conversion

A diverse range of problems, along with intriguing prospects, exists for the conversion of CO_2 into frequently utilized formal products. Despite CO_2 being a plentiful and inexpensive source, its chemical inertness frequently makes conversion procedures energy-intensive and economically impractical at large scales. Recent advancements in catalysis, electrochemistry, and process engineering are generating new opportunities for effective CO_2 usage for methanol production (Fig. 17).



Fig. 17 Different Challenges and possibilities of CO_2 to methanol conversion (with various catalysts used).



(i) CO₂ is a linear, kinetically inert, nonpolar molecule with two opposite reactive sites, *i.e.*, carbonyl carbon has an electron-donating nature, and oxygen is an electron withdrawing species. Therefore, breaking the two double bonds present in the inert CO₂ molecule requires a higher energy, which poses the main challenge for the reduction of CO₂ to methanol.²⁵⁷ The conversion of CO₂ to CO or other value-added products is facilitated using the metal surface catalysts.²⁵⁸

The methanol synthesis from CO₂ generates water as a byproduct, which directly influences the rapid sintering and deactivation of the Cu/ZnO catalyst. As a result, if the RWGS reaction occurs at a high temperature, it continues in an endothermic mode, and if it occurs at a lower temperature, it reduces the catalytic activity, which can be considered the main drawback of CO₂.^{69,259,260}

(ii) Intermediate stabilization

In methanol synthesis from the hydrogenation of CO₂, controlling the intermediate stabilization is another critical challenge. CO is a crucial intermediate in the catalytic hydrogenation of methanol synthesis. From a thermodynamic perspective, the bonding between CO and the catalyst surface develops a stronger binding energy that increases the reaction rate of methanol or any other hydrocarbon synthesis process, while the bonding between the catalyst surface and CO initiates the RWGS reaction with weaker binding energy.²⁶¹ For methanol synthesis, controlling the stabilization of the intermediate, *i.e.*, CO, is crucial for increasing the yields.¹²³ DFT calculations and studies reveal that multiple factors influence catalytic properties. These include the key intermediate, oxygen adsorption energy, the relationship between catalyst structure and properties, and CO₂ adsorption phenomena. This understanding provides a novel approach for catalyst development.³⁹³

(iii) Inhibition of hydrogenation by water

The production of large amounts of water during the reduction of CO₂ by H₂ reduces the catalytic activity of the catalyst through the formation of hydroxyl. The main challenge of researchers is to develop a hydrothermal catalyst that resists catalyst poisoning. However, some research groups improved the catalytic activity of methanol production from CO₂ by using promising noble metals, primarily Pd, Pt-based microporous SiO₂-supported catalysts, and carbon shell-supported catalysts.^{394,395}

(iv) Development of economically favorable catalysts

One of the challenges researchers face is developing a low-cost, economically advantageous catalyst with good recycling and reducible qualities that would produce large amounts of methanol from the CO₂ hydrogenation process.³⁹⁶ Recently, some research groups developed a Mo₂C catalyst; however, this catalyst's main disadvantage is coke formation because, during the reaction, it binds firmly to intermediate hydrocarbons.³⁹⁷

(v) CO₂ reduction by alkanes

Researchers are trying to develop an alternative path for the reduction of CO₂. An alternate substance that can be used to reduce CO₂ might be light alkanes.³⁹⁸ Although methane dry reforming can be employed as an alternative to hydrogen gas, researchers have observed that the catalyst rapidly loses effectiveness when exposed to elevated temperatures. But in the case of ethane, thermodynamically favorable conditions are

available for CO₂ hydrogenation. In the near future, one of the hotspot research topics for energy engineering would be CO₂ reduction *via* light alkanes.³⁸⁹

7. Conclusion & future perspectives

This review emphasizes the use of noble metal-based catalysts for the hydrogenation of CO₂ to produce methanol. It is evident that several aspects of catalysts are important including promoters, support types, synthetic procedures, reaction circumstances, large surface area, and particle size, all of which must be taken into consideration to design catalysts to achieve higher performance.

The “Methanol Economy” offers a promising strategy for addressing global warming by utilizing CO₂ as a renewable energy resource. Methanol can serve as an energy storage medium, hydrocarbon feedstock, and alternative fuel. Various catalysts, including those based on noble metals, have been developed for the hydrogenation of methanol from CO₂. The conversion of CO₂ to methanol using heterogeneous and electrochemical catalysts holds industrial promise but faces significant challenges. Heterogeneous catalysts, such as noble metal-based systems, are advantageous due to ease of separation and recyclability but are hindered by mass transport and diffusion limitations. Electrochemical catalysts offer high selectivity and efficiency but require precise control of operating conditions and are sensitive to electrode materials and electrolytes. Nanostructured catalysts can enhance surface area and tunability, improving reaction rates and stability. However, scaling these technologies from lab to industry involves challenges in reactor design, mass transport, and heat management, essential for commercial viability. Addressing these issues is crucial for the success of CO₂ to methanol conversion technologies. The procedure's efficacy depends on understanding fundamental chemistry, catalyst characterization, and reactor characteristics. Researchers aim to develop dual-function promoters to improve CO₂ to CH₃OH conversion and reduce CO *via* the RWGS reaction. While noble metal-based catalysts show exceptional efficacy, their limited activity and high cost make them economically impractical. To commercialize CO₂-derived methanol synthesis, researchers need to integrate multiple elements into a single material or process. This may involve creating innovative materials that combine the catalytic abilities of noble metals with more abundant and cost-effective components, enhancing efficiency and reducing costs. Additionally, improving reactor designs to increase CO₂-catalyst interaction could further boost conversion rates and overall feasibility.

The hydrogenation of CO₂ to methanol, despite its limitations, offers promising pathways for sustainable fuel production. Although progress has been made in understanding reaction mechanisms and catalyst design, critical areas still require further research. This study establishes a foundation for sustainable fuel production methods, potentially reducing fossil fuel dependence. By identifying key areas for future research, it paves the way for advances in CO₂ utilization and catalyst design, which could significantly impact climate



change mitigation and the shift to sustainable energy. Priority areas include developing low-temperature reactive catalysts, optimizing reaction conditions and reactor designs, and employing guided rational catalyst design and synthesis. Future efforts may utilize advanced analytical techniques and computational methods to further elucidate reaction mechanisms. Bridging the gap between model catalysts and industrial-scale processing remains crucial for commercialization. The field shows promise through the development of novel materials, particularly noble metal-based catalysts, and the exploration of energy-efficient technologies. Ultimately, achieving sustainable methanol production from CO₂ hydrogenation will necessitate interdisciplinary collaboration and innovative strategies to overcome existing challenges, contributing significantly to global initiatives aimed at reducing atmospheric CO₂.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Author contributions

Soumalya Roy: conceptualization, investigation, data generation, and writing—original draft. Ezhava Manu Manohar: administration and data validation. Dr Sujoy Bandyopadhyay: administration and data validation. Dr Manik Chandra Singh: administration and data validation. Yeji Cha: administration and data validation. Dr Soumen Giri: writing and editing. Dr Sharad Lande: writing and editing. Dr Kyungsu Na: conceptualization, result validation, supervision, writing, editing, and methodology. Dr Junseong Lee: conceptualization, result validation, supervision, writing, editing, and methodology. Dr Sourav Das: conceptualization, result validation, supervision, writing, editing, and methodology.

Conflicts of interest

The authors declare no competing financial interest.

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