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REVIEW

Carbon dioxide valorization: paving the way for climate change mitigation and a sustainable future

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Abstract

The global rise in carbon dioxide (CO_2) emissions, primarily from the combustion of fossil fuels, poses a major barrier to meeting the Paris Agreement target of limiting global warming to 1.5 °C. A transition to a low-carbon economy is essential to mitigate climate change and its potential consequences. Carbon capture, utilization, and storage (CCUS) technologies offer promising solutions by capturing CO_2 from major emission sources and converting it into valuable chemicals and materials. This review provides a comprehensive overview of key CO_2 sources and recent developments in CO_2 capture technologies, encompassing chemical absorption, adsorption on solid materials, chemical looping, and membrane separation. Additionally, it explores various pathways for CO_2 conversion into high-value products, such as methanol, dimethyl ether, acetic acid, and synthetic fuels, alongside emerging applications like graphene, cyclic carbonates, and alkyl/aryl carbamates. The potential of syngas production and the emerging photocatalytic reduction of CO_2 are also discussed. The review also discourses the challenges to the widespread adoption of CCUS technologies, encompassing economic, technical, and infrastructural barriers, while highlighting prospects for enhancing their implementation. Environmental trade-offs such as water and resource intensity, lifecycle emissions, and risks of CO_2 leakage are addressed to ensure sustainability. The review underscores the alignment of CO_2 valorization technologies with the global climate goals. By fostering technological advancements, policy support, and international cooperation, CCUS can serve as a transformative pathway to mitigate climate change, reduce industrial carbon footprints, and drive sustainable innovation across sectors, achieving the environmental, economic, and societal sustainability.

Keywords Carbon dioxide valorization · Climate change mitigation · CO_2 capture and utilization (CCU) · Catalytic conversion of CO_2 · Sustainability approaches

Introduction

The ongoing rise in atmospheric CO_2—from ~ 275 ppm in the pre-industrial era to over 420 ppm today—has been a major driver of global warming (Ozkan 2024). CO_2 accounts for the largest share of anthropogenic greenhouse gas (GHG) emissions, with the energy sector contributing approximately 75.6% of global emissions (Aneesh and Sam 2023). An estimated 47.5 billion tons of GHG are released annually into the atmosphere, of which 34.73 billion tons are CO_2. The energy sector is responsible for about 75.6% of the worldwide GHG emissions. Over the last century, atmospheric CO_2 levels have increased dramatically due to the unchecked exploitation of fossil fuels, industrialization, and widespread deforestation (Hansen et al. 2025). The Intergovernmental Panel on Climate Change (IPCC) estimates that by 2100, the atmosphere might contain as much as 570 parts per million of CO_2, which would result in an increase in the average world temperature of around 1.9 °C and a rise in the average sea level of 3.8 m (Song et al. 2019). According to the published estimates of International Energy Outlook on 2011, the energy-related carbon dioxide (CO_2) emissions would reach 43.2 billion metric tons by 2035 (Shakya et al. 2023), where, 30% of the emitted anthropogenic CO_2 are

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related to the industrial activities (Leeson et al. 2017). The massive increases in CO_2 emissions (over 40 Gt CO_2 annually) found to be coincided with the massive levels of fossil fuel consumption (Demir et al. 2022). Moreover, according to Hou et al., (2022), around 50 billion tons of the GHG are released annually into the atmosphere worldwide; since the mid-1800s, this amount has increased fifty times. Of these emissions, 73.2% are attributable to energy use (in transportation, 16.2%, buildings, 17.5%, and industry, 24.2%), 18.4% are from land use and agriculture, and the remaining 8.4% are from direct industry (chemicals and cements, 5.2%) and waste (landfills and wastewater, 3.2%). The main contributors for direct industrial CO_2 emissions are cement, iron, steel, and chemical industries, which account for approximately 70% of the direct industrial CO_2 emissions (Roussanaly et al. 2021). Figure 1a represents the breakdown of the sources of CO_2 emissions as reported by Song et al. (2019). Fossil fuel utilization for power generation constitutes around 40% of total energy- associated CO_2 emissions (Alli et al. 2024). The transportation sector contributes roughly 20% of global CO_2 emissions, predominantly from road traffic (Azhar et al. 2024). The direct CO_2 emissions from industrial sector are expected to grow reaching approximately 10 $GtCO_2$ by 2060 (Roussanaly et al. 2021). Figure 1b elucidates the highest contributors in CO_2 emissions, which are; China, USA, India, Russia, and Japan (Dziejarski et al. 2023). However, the USA continues to be the historical largest cumulative emitter, produced

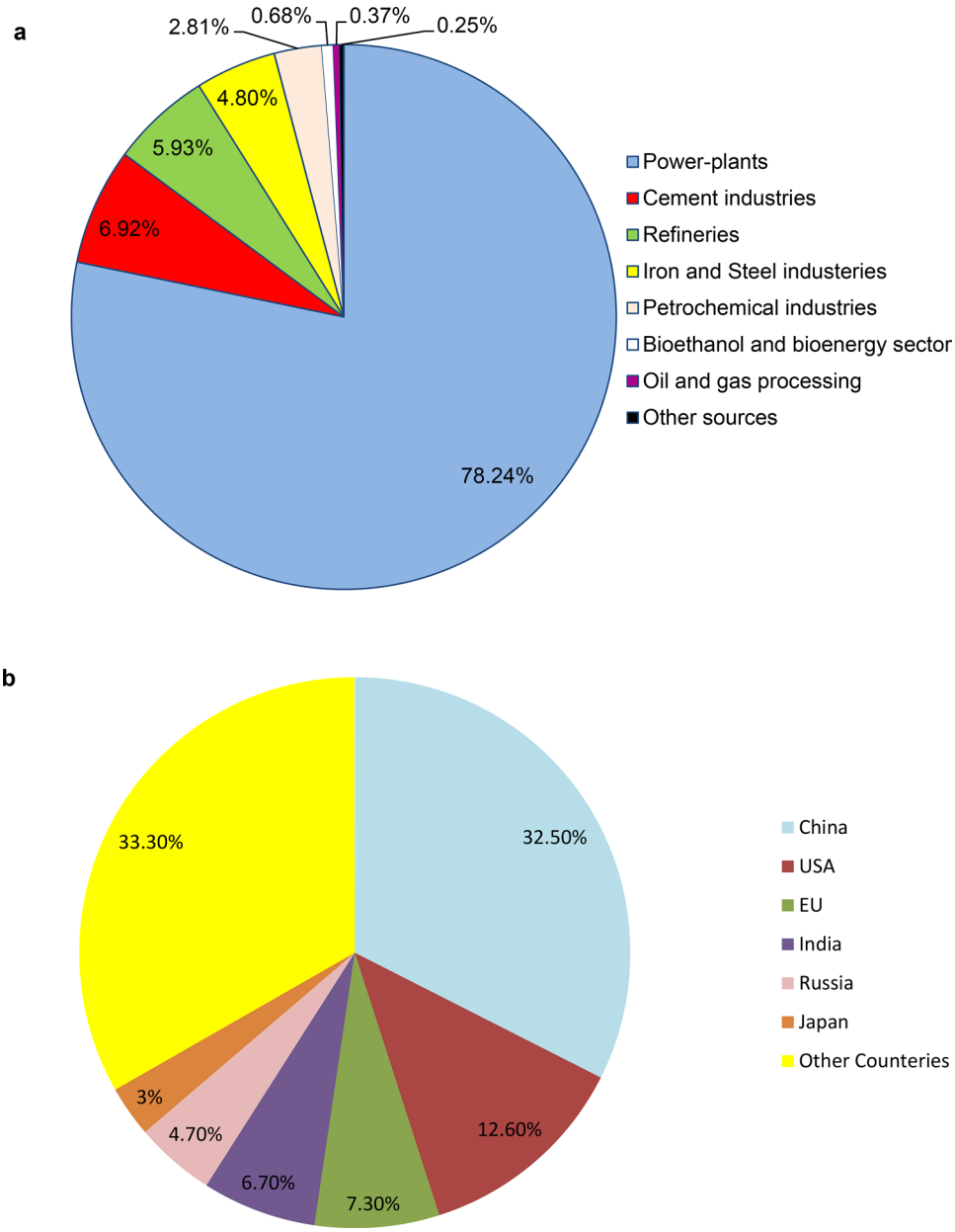

Fig. 1 **a** The sources of CO_2 emissions. **b** The main contributors to the worldwide CO_2 emissions

approximately 410 billion metric tons, followed by China, Russia, Germany, and UK, which recorded 220, 113, 92, and 78 billion metric tons, respectively. In terms of absolute emissions, the top three countries are China, the US, and the EU's member states, while, Russia and the United States have the highest per capita emissions of GHG (Dziejarski et al. 2023). Yet, Hanifa et al. (2023) reported that the highest CO_2-contributors within 2005 and 2021 are USA, China, EU, and India.

The obvious consequences of climate change in the twenty-first century and the global agreement that it is directly dependent on CO_2 emissions accelerate the need for emission reduction solutions to be implemented as soon as possible. It has been reported that, to maintain the temperature increase below 2 °C relative to preindustrial levels, a reduction of CO_2 emissions of 41–72% by 2050 and 78–118% by 2100 is required compared to the GHG levels of 2010 (Azhari et al. 2022). IPCC projections also indicate that to restrict global warming to below 1.5 °C, a 43% decrease in GHG is required by 2030 (Ioannou et al. 2023). Moreover, for the successful achievements of seventeen goals of sustainable development (SDGs) with its economy, society, and environment pillars, which were implemented by the 193 United Nations' members states in 2015 (Ioannou et al. 2023), there is a mandatory shift from the brown economy of high carbon footprint towards the circular economy, green economy, and bioeconomy of low carbon footprint (Mujtaba et al. 2023). Consequently, in the next ten years, there must be swift and significant changes made to the energy, land, urban, and industrial systems in order to meet the 1.5 °C Paris objective and reaching and net-zero CO_2-emission by 2050 (Soo et al. 2024). Thus, amidst the global fight against climate change, cutting-edge, novel solutions are badly needed to reduce GHG emissions, limit the rise in average surface temperatures to less than 2 °C, and preserve the environmental sustainability (Demir et al. 2022). Owing to the dearth of substitutes for upcoming low-carbon plants, post-combustion carbon capture decarbonization is deemed increasingly significant in different industrial sectors. With a high capture efficiency (> 90%), liquid amine absorption is a proven method that has been used in the commercial sector to capture post-combustion carbon from various emission sources (Leung et al. 2014). Nevertheless, it is less advantageous for future industrial systems because to the drawbacks of a large chemical footprint and a high energy need for absorbent regeneration (Hou et al. 2022). In fact, it is predicted that amine-based post-combustion CO_2 capture processes add an energy penalty of 30% to a power plant's output, requiring the use of alternate strategies for energy efficiency (Demir et al. 2022). Yet, with its simplicity, minimal physical and chemical footprints, low energy consumption, minimal carbon impact, high modularity and flexibility, membrane technology has drawn more attention to itself in the last few decades for the purpose of capturing and sequestering carbon dioxide (Guo et al. 2022).

Reducing the anthropogenic GHG emissions, particularly CO_2, is one of the most difficult environmental problems associated with climate change. Meeting these targets demands a shift from high-carbon to circular, bio-based, and green economies. Rapid systemic changes in energy, industry, and urban infrastructure are necessary. To cut CO_2 emissions, four strategies can be used: increasing energy efficiency; moving to renewable and less carbon-intensity energy; utilizing carbon capture and storage (CCS); and implementing carbon capturing, usage, and storage (CCUS). The advanced CCS is one such cutting-edge technology that has the potential to change entire industries (Beck 2020). CCS has the main advantage that it is capable of consuming fossil fuels constantly without producing a noticeable rise in CO_2 emissions (Budinis et al. 2018). According to the IPCC, CCS is "an essential technology" for achieving the world's climate goals. As of right now, the most promising technique for cutting GHG emissions is carbon capture, usage, and storage, or CCUS (Ferdoush et al. 2024). CO_2 can be extracted from oil and gas refineries, power plants, and industrial sites using CCS. For example IPCC estimated the reduction of emitted CO_2 by approximately 80–90%, upon the integration of CCS in the power plants (Posada-Pérez et al. 2023). In addition to the obvious benefits of lowering CO_2 emissions, CCS technology supports industrial decarbonization initiatives, enhances air quality by absorbing other pollutants released during combustion. Moreover, it acts as a bridge technology leading to more sustainable and clean energy in the future (Mwenketishi et al. 2023). The United States of America, China, and Russia are the top three countries in the Global CCS Institute's Inherent Interest in CCS due to their economies' reliance on fossil fuels (Karousos et al. 2020). This index is based on the proportion of production and consumption of fossil fuels and indicates whether an economy is suitable for the large-scale deployment of CCS to decarbonize and expand its energy production. However, Canada is considered the world leader in creating an enabling environment for the large-scale deployment of CCS. On the other hand, Canada is regarded as the comprehensive leader in establishing favorable conditions for the widespread implementation of CCS (Karousos et al. 2020). It is noteworthy that the Government of Norway, in collaboration with Equinor, Shell, and Total, initiated the Northern Lights project to provide an "open source" service for the transportation and storage of CO_2 emissions from Europe. The project's overall goals will be greatly impacted by the implemented CO_2 separation methods (Karousos et al. 2020). European scenarios aim to by 2050 at least 50% of Nordic cement plants must fully implement CCUS, alongside with 30% of steel, iron, and chemical facilities. The implementation of CCUS is expected to facilitate a

requisite 60% decrease in carbon dioxide intensity within the industrial sector (McLaughlin et al. 2023).

The globe remains significantly far from achieving the Paris Agreement objective of restricting global temperature increase to 1.5 °C by the end of the twentieth century. It is unavoidable to transition to a lower-carbon economy in order to slow down global warming and avoid the possibly catastrophic repercussions of climate change. This review summarizes the applied CO_2-capturing approaches that support sustainable development and climate mitigation. It provides a preliminary overview about the conversion of CO_2 into valued products, to enrich the circular carbon economy, close the carbon cycle, and decrease the net emissions.

Headways in capturing technologies

CCS is classified based on the capture process category (pre-combustion, post-combustion, and oxy-combustion) and the separation technology type (absorption, adsorption, cryogenic distillation, membranes, chemical looping, and gas hydrates) (Narindri Rara Winayu et al. 2023). Although post-combustion capture technology is extensively implemented (Pancione et al. 2024), however, oxy-combustion capture is in the developmental stage and it is not yet commercially viable, while, the pre-combustion capture is anticipated to be decades away from the commercial feasibility (Ahmed et al. 2025).

Chemical absorption is a technique that captivates CO_2 from flue gas using a chemical solvent. After that, the solvent is renewed and utilized to absorb more CO_2. Although of its high cost and energy intensiveness, in the upcoming years, chemical absorption practice is anticipated to be the most widely used CCUS technology (Karayil et al. 2024).

Adsorption on solid materials is a technique that depends on the interactions between gases and porous materials and allows for the storage and/or separation of gases. For economical and effective gas separations, an adsorbent should ideally have; high selectivity, stability, adsorption capacity, and regenerability, besides, quick adsorption kinetics, scalable synthesis process and cheap cost (Raganati et al. 2021). However, discrepancies between these metrics can affect the adsorbent performance and its industrial applicability, for example, a material with high selective may have a limited working-capacity, which could render the separation process economically unfeasible (Karayil et al. 2024).

Cryogenics is a technique that liquefies CO_2 at low temperatures. After that, the liquefied CO_2 is either piped or kept in tanks. Although it works well for CO_2 heavy streams, it can also cause pressure build-up, clogging, and a reduction in heat transfer rate (Sreenivasulu et al. 2015). Cryogenic separation may become less appealing for certain gas separations as a result of these issues as well as the high energy expenditures associated with operating at low temperatures (Fan et al. 2021).

Chemical looping technology is another significant development in this field that could completely replace the requirement for carbon capture devices (Li et al. 2017). Chemical looping creates a flue gas that is almost completely CO_2 by transferring oxygen from the air to fuel using metal oxides. It is currently in the early stages of development, but it could be less energy-intensive and more effective than chemical absorption. This approach is more attractive because it outperforms oxyfuel combustion in terms of efficiency and can be retrofitted into current power-plants and industrialized practices. Among the other potential technologies is the ionic liquid and membrane combo (Dai et al. 2016a,b).

Membrane separation is a technique that separates CO_2 from flue gas specifically by letting it flow through more easily than other gases. Since the gases penetrate the membrane's holes at varying rates, separation is made possible by the pressure differential across the membrane, which normally drives the gas flow (Guo et al. 2022). There are many publications concerning with the CO_2-selective facilitated transport membrane (Carapellucci and Milazzo 2003; Hägg and Lindbrathen 2005; Huang et al. 2008; Yang et al. 2008; Brunetti et al. 2010; D'Alessandro et al. 2010; Guo et al. 2022). Nevertheless, there are still issues with using membranes for CO_2 capture (Lin and Freeman 2005). These issues stem from two things (He et al. 2014; 2015): (1) the poor membrane stability and short lifetime when exposed to a gas stream containing the impurities of acid gases like SO_2, NOx; and (2) the trade-off between most polymeric membranes' selectivity and gas permeance, which limits the efficacy of membrane separation. Therefore, it is necessary to design high-performance membranes with minimal material costs and great stability. The qualities of the membrane material, the flow rate of feed gas and its composition, the process operational conditions, and the separation needs are the primary determinants of selecting an appropriate membrane material for a given application (Ramasubramanian and Ho 2011). The most important characteristics required upon the selection of membrane for CO_2 separation are; high CO_2 selectivity and permeability, the good stability of the membrane material and resistance against plasticization and aging, besides, the reproducibility and sustainability of the production process to stabilize the cost of fabrication when scaling up (Torre-Celeizabal et al. 2022). There are two main types of membranes; mixed matrix membranes (MMMs) and fixed-site-carrier membranes (FSCM) (Demir et al. 2022). The MMMs are composed of polymeric and inorganic particles that uniformly interpenetrate one another (Chung et al. 2007). Despite being extensively utilized because of their easy processing, low cost, and scalability, polymeric membranes suffer from aging, plasticization, and typically have

poor thermal and chemical stability, that hinder their gas separation capabilities (Kamble et al. 2021). Furthermore, polymeric membranes exhibit trade-offs between permeability and selectivity, telltale achieving both high permeability and selectivity challengeable (Demir et al. 2022). Nevertheless, the common membrane materials for CO_2 capturing from flue gas in hollow fiber membrane contactors are polypropylene (Dindore et al. 2005; Al-Marzouqi et al. 2008; Zhang et al. 2008; Faiz and Al-Marzouqi 2009; Goyal et al. 2015), polytetrafluoroethylene (Faiz and Al-Marzouqi 2010; Khaisri et al. 2010; Marzouk et al. 2010). polyvinylidene fluoride (Zhang et al. 2008; Faiz and Al-Marzouqi 2009; Chabanon et al. 2013; Farjami et al. 2015; Mehdipourghazi et al. 2015), and polymethylpentene (Chabanon et al. 2013). The benefits and disadvantages of the primary CO_2 capture techniques are summarized in Table 1.

It should be mentioned that the field of carbon capturing (CC) uses both chemical and physical solvents (Soo et al. 2024). Upon the application of physical solvent, the system is based solely on gas solubility, there is no chemical reaction. However, upon the introduction of a chemical solvent, a chemical reaction occurs on the solvent side (Rivero et al. 2020). Examples of the typical solvents for CO_2 capturing from flue gas in hollow fiber membrane contactors (HFMCs) are; water (Al-Marzouqi et al. 2008; Faiz et al. 2011), sodium hydroxide (Dindore et al. 2005), monoethanolamine (Paul et al. 2007; Faiz and Al-Marzouqi 2009; Sohrabi et al. 2011; Chabanon et al. 2013; Luis 2016; Ho et al. 2022), diethanolamine (Zhang et al. 2008; Goyal et al. 2015; Waseem et al. 2025), and Methyldiethanolamine (Shirazian et al. 2012).

Even though CCS technology is still relatively young, a number of improvements have already been made, all aimed at increasing its effectiveness and affordability. The development of capture technology, which focuses on capturing CO_2 emissions from diverse sources such as power stations, industrial sites, and direct air capture, has been one of the most important advances in CCS. Currently, R&D on CCS targets a cost of $40–60 per ton of CO_2 to ensure the practical and economical large-scale implementation (Soo et al. 2024). The development of novel materials and procedures that can raise capture efficiency, lower energy requirements, and cut prices is a priority (Ozkan 2024).

Examples for CO_2 capturing and utilization systems

EOR has proven safe geologic storage, can lower life-cycle emissions per barrel of oil, and has encouraged the use of CCS, proving that the price of carbon may influence the adoption of new technologies (Novak Mavar et al. 2021). The EOR has assigned a value for CO_2, which was estimated to be around \$15 t/CO_2 (IEA 2019). However, only around 30% of the CO_2 used for EOR is reported to come from human sources; the remainder is extracted from natural resources (IEA 2015). Therefore, it would make sense to work towards replacing mined sources with anthropogenic ones, expanding the market for capturing, or imposing a maximum CO_2 storage requirement per barrel of oil produced (Sambo et al. 2024). Nevertheless, ammonia production plants are also expected to grow to be the biggest geologic storage undertaking (Beck 2020) and the integration of ammonia production plants with urea production plants is a very feasible CCUS (McLaughlin et al. 2023).

Industries are currently actively looking for workable solutions to meet their net-zero goals as CCUS gains traction. That comes in parallel with the increasing

Table 1 The benefits and drawbacks of CO_2 separation techniques

Method	Promises	Challenges	Reference
Absorption	• Advanced technology • High rate of CO_2 removal • Operates at ambient conditions	• Hefty regeneration expenses • Possible corrosion • Degradation of solvents	Song et al. (2019)
Adsorption	• Numerous adsorbents • Efficient adsorption capability • Various modes of operation	• Decrease in pressure • Sensitivity towards impurities • Instability of sorbents	Li et al. (2011)
Cryogenic	• No chemical solvents • No secondary pollutants • Ideal for streams containing high concentrations of CO_2 • Applicable for large-scale processes	• Expensive equipment for severe circumstances • Exorbitant operating costs in harsh circumstances • Possible heat transfer and plugging issues	Sreenivasulu et al. (2015)
Membrane separation	• Higher separation efficiency • Low capital and operating costs • Low carbon footprint • Operational simplicity	• Elevated membrane cost • Low applicability at elevated temperature • Sensitivity towards impurities	Chuah et al. (2018)

attention being paid to "blue hydrogen", which is just another improvement that is quickly gathering momentum (Ram and Salkuti 2023). Thus, the production of blue hydrogen using CCS technology has increased dramatically, and is considered as a cost-effective start to reach net-zero emissions (Riemer and Duscha 2023). That can be performed by separating natural gas into H_2 and CO_2 using techniques like auto-thermal reforming (ATR) and steam methane reforming (SMR) (Beck 2020). Blue hydrogen is considered as a cleaner alternative, since it minimizes environmental damage and bargains almost zero emissions by limiting the GHG. This technology has a great deal of promise to cut emissions in a number of sectors, including transportation, power generation, oil and gas, and other industrial uses. Blue hydrogen is essential to closing the gap towards a more sustainable future since it reduces emissions and offers a dependable source of energy (Cavalcante et al. 2024).

In addition to these advances, research on renewable energy is still thriving (Fikru et al. 2024). Innovative technologies, like more sophisticated solar panels, more effective wind turbines, and cutting-edge energy storage systems, are being actively explored and developed by scientists and specialists. It is crucial to remember that these renewable energy sources are sporadic, which means that they are unable to reliably offer a consistent amount of electricity. As a result, the incorporation of CCS technology becomes essential to support and guarantee a stable, sustainable energy environment that reduces carbon emissions (Hanson et al. 2025). As previously mentioned, the development of membrane materials typically entails a variety of techniques to design materials with high CO_2 permeability and selectivity at the same time. These membranes are often produced as thick, self-supporting films in laboratories. Subsequently, intriguing materials are created as thin-film composites (TFC) on porous supports, and their ability to separate using gas mixtures as feed gas is assessed (Janakiram et al. 2022). Most of the time, there is a lack of a cooperative opportunity to create an ongoing feedback loop between technology developers and possible end users, or there is a membrane development gap between lab-based research and industrial requirements (Leeson et al. 2017). Due to these constraints, only a limited number of membrane materials are eventually evaluated and scaled up under circumstances relevant to the intended end users (Dai et al. 2019). Depending on the needs of the end users, the upgraded modules should handle incoming flue gas and produce certain targets of CO_2 capture rate and CO_2 purity. The usage of the purified stream determines the typical CO_2 capture targets; that is, the amount of storage and transportation needed is typically greater than 98% and varies depending on the specific use case. Since commercially available membranes have a selectivity of less than 50 for CO_2/N_2, most applications need a two-stage membrane method to address both targets concurrently (Janakiram et al. 2022). It should be mentioned that during the past 20 years, there has been a growing interest in the study of gas permeability and selectivity performance through inorganic membranes in high-pressure settings (Karousos et al. 2020).

Another new coming CCUS is the conversion of CO_2 into biofuels (Nawkarkar et al. 2022) and different value-added products via micro- and macro-algae (El-Gendy and Nassar 2021; Nguyen et al. 2023; El-Gendy et al. 2023; 2024; Li and Yao 2024; Yang et al. 2024). Algal biomass as a natural resource capturing CO_2 can be valorized into organic fertilizer (Gurau et al. 2025), and animal fodder (Iglina et al. 2022). Besides, the synthetic fuels, i.e. artificial fuels or e-fuels production via Fischer–Tropsch can be done using carbon dioxide, renewable energy, and water (Samavati et al. 2018; Gao et al. 2021; Ram and Salkuti 2023).

An increasingly accurate prediction of a CO_2 capture system can be achieved by using membrane module performance data collected in an industrially relevant setting as the groundwork for process simulation, and some simulation trainings that employed multi-stage cascade systems to reach highest CO_2 recovery and purity have been reported. For example; Franz et al. (2013) used permeance data from commercial PolyActive membrane modules to investigate the impact of sweep gas on a cascaded membrane process at a reference scale 600 MW power plant. Low et al. (2013) investigated the impact of humidity on CO_2 separation utilizing thermally rearranged PBI membranes and PVAm/PVA assisted transport, with a flue gas capacity of 100 Nm^3/h. He et al. (2015) conducted a feasibility analysis using 18,260 kmol/h of refinery flue gas in order to achieve a > 80% CO_2 capture ratio and > 95% CO_2 purity. They did that by employing pilot scale data of fixed site carrier polyvinylamine membrane. Hollow fiber precursors based on cellulose were used to prepare a novel carbon molecular sieve hollow fiber membrane (Karousos et al. 2020). Upon its application for gas separation, the CO_2/N_2 at 10% v/v CO_2, 25 °C, and 8 bar(a) had the greatest yielding mixture selectivity values of 42, and the CO_2/CH_4 at the same conditions had values of about 150 with a corresponding CO_2 permeabilities of 110 and 45 Barrer, respectively. Furthermore, studies with different head pressures while keeping the trans-membrane pressure and differential pressure at 8 bar(a) have shown that the CO_2/N_2 separation factor can be further improved, with actual selectivity reaching 55 and permeability reaching 180 at 20 bar head pressure, but the CO_2/CH_4 separation was found to be barely affected. This is considered as a significant discovery because treating natural gas—that is, sweetening and purifying it—is both economically and energetically advantageous when done in the circumstances where the natural gas stream is retrieved from the wells or following a decompression. The regeneration of membrane was easily performed by heating under helium flow for 24 h. According to a performed

process simulation, it is technically possible to create 96% methane with a low methane loss of less than 4% using a two-stage carbon membrane system. The implemented novel cellulose based-carbon molecular sieve hollow fiber membranes grants a prospective industrial applicability for gas separation and also in high-pressure natural gas sweetening plants (Karousos et al. 2020). Chavan et al. (2021) reported a unique hollow fiber membrane contactor method for removing CO_2 from a mixture of gases to obtain a competitive recovery and high purity for poorly soluble gas (H_2, N_2, or CH_4) and investigated its success both theoretically and empirically. Briefly, the theoretical model was developed to demonstrate how the dissolved residual CO_2 reduces the absorbent's capacity during regeneration. That model was supported by experimental research, which demonstrated that it is still difficult to achieve a purity > 99% in a closed loop system without using excessive chemicals or energy. Further, an unique approach called pH swing absorption was applied, which entails infusing a moderate amount of acid and base to alter the acido-basic equilibrium of CO_2 throughout the absorption and desorption stages. By changing CO_2 into its ionic equivalents (HCO_3^- or CO_2^{3-}) prior to absorption and enhancing CO_2 degassing prior to desorption, it seeks to reduce the amount of residual CO_2 in the regenerating absorbent. The performance's dependence on operating parameters like liquid flowrate and total gas pressure was also demonstrated by the results. For the N_2/CO_2 combination that suggested method yielded a N_2 recovery rate and purity of 94.13% and 99.97%, respectively, while for the H_2/CO_2 mixture, a maximum H_2 recovery rate and purity of 93.96% and 99.96% were achieved, respectively. Furthermore, the suggested patented method might result in less energy or chemical usage.

However, Janakiram et al. (2022) reported the significance of utilizing ideal combinations of membranes with various levels of separation efficiency at various phases. Not only that, but it was also discovered that the system's effectiveness was greatly impacted by the placement of membranes with various characteristics at various phases. Both theoretical and practical investigations were done also by Ho et al. (2022) on the CO_2 absorption efficiency of hollow-fiber membrane contactors utilizing an ethanolamine solvent under concurrent- and countercurrent flow conditions. In a work reported by Liu et al. (2022) the CO_2-EOR related gas from oilfields was treated using a pretreatment system in conjunction with a single-stage membrane process. In order to assess and improve the membrane separation performance, a mathematical model of the hollow fiber membrane separator was created. The simulation result produced using MATLAB Simulink was compared to findings from the literature and a field test conducted at an oilfield using a pilot plant to validate the model. Next, using three different membrane materials—cellulose acetate (CA), polyimide (PI), and polysulfone (PSF)—the consequences of membrane operating and fundamental performance parameters on CO_2 purity, CO_2 recovery, and CH_4 loss rate were investigated using the created model. It was found that the CO_2 recovery increased and the CO_2 content in the permeate decreased when the other conditions were the same and the membrane permeance was raised. Thus, when choosing appropriate membrane materials, it is crucial to strike a balance between CO_2 recovery and purity, which are influenced by permeance and separation coefficient. Moreover, PI demonstrated the overall optimum range of CO_2 concentration in feed gas under the parameters examined in that work, which included an operating temperature of 45 °C, a CO_2 concentration in the associated gas of 20–80%, a feed pressure of 0.5–1.0 MPa, and a membrane effective surface area of 50–550 m^2. Furthermore, PI needed a smaller effective surface area and could function well across a wider range of feed pressures.

Membrane Technology and Research, Inc. (MTR) used a sizable pilot system to test their highly permeable ultrathin PolarisTM membranes for CO_2 capture in a 1-MW coal-fired power plant. Furthermore, the NanoGLOWA project (EUFP6) created high-performance fixed-site-carrier (FSC) membranes for CO_2 separation. The Membrane Research team (Memfo) at NTNU tested a small pilot-scale system for CO_2 capture from flue gas at the Sines coal-fired power plant in Portugal in 2011; the system's stable performance over a 6-month period was reported (Sandru et al. 2013). Their most recent pilot system, which used 20-m^2 hollow fibers, was tested for CO_2 capture at the Norcem cement factory (Hägg et al. 2017). Furthermore, Helmholtz-Zentrum Geesthacht tested a 10-m^2 PolyActive® membrane module for CO_2 capture (Pohlmann et al. 2016). Pre-pilot scale membrane modules with hollow fiber configuration hybrid assisted transport membranes have been claimed to capture CO_2 from an actual slipstream flue gas in the Colacem cement factory in Gubbio, Italy (Janakiram et al. 2021).

Additionally, a few cutting-edge separation techniques have been developed for CO_2 capture and have shown promise for cost savings (Shakya et al. 2023). That based on the high CO_2 solubility in ionic liquids (Zhang et al. 2012), microporous materials of zeolites and alumina, as solid adsorbents (Jeon et al. 2017), metal oxides applications in the chemical looping cycle, metal organic frameworks (MOFs) (Demir et al. 2022), and other mesoporous solid adsorbents grafted with aminosilanes and impregnated with polyamines (Yu et al. 2012).

Carbon membranes which are ultra-microporous inorganic membranes are mostly made by carbonising polymeric precursors. They have a moderate modulus, strong mechanical strength, and excellent gas selectivity, primarily for H_2 and CO_2 (Lei et al. 2019). Carbon membranes offer several benefits, primarily because of their low production costs, great selectivity, and well-established understanding

of the formation of controlled porous structures (Yoshimune and Haraya 2019). Indeed, carbon molecular sieve membranes (CMSMs) appear to be a potential candidate material for CO_2/CH_4 and CO_2/N_2 separations due to their superior separation performance and stability. High gas selective carbon membranes have been constructed thus far using a variety of polymeric precursors, primarily polyimides (PI) and cellulose derivatives (Favvas et al. 2017). Building upon advancements in membrane technology for CO_2 capture, the integration of captured CO_2 into value-added chemical production presents a transformative opportunity for addressing climate change and advancing sustainable practices. Captured CO_2 can be utilized as a feedstock for synthesizing various chemicals such as methanol, urea, and carbonates, which are widely used in industries ranging from agriculture to construction (Gupta et al. 2024). Valorization of CO_2 into urea and methanol is considered feasible, utilizing around 110 million tons of CO_2 annually (Biswal et al. 2022). The high purity of CO_2 obtained from membrane-based separation processes enhances the efficiency of catalytic and electrochemical reactions employed in these conversions. Promising materials for gas separation applications have also been described recently, including supported graphene oxide membranes (Zhu et al. 2017) and MXene membranes, a relatively new family of 2D materials (Ding et al. 2023). In the upcoming decades, inorganic membranes that are substantially more resilient and have fewer environmental effects than polymeric membranes will become more and more crucial in a variety of membrane separation processes (Wu 2019). However, those cutting-edge materials are still in the early stages of research, and more has to be done to look into the up-scaling problem and material cost. These initiatives have raised the technology readiness levels (TRL) of membrane technology for post-combustion CO_2 capture. The high purity of CO_2 obtained from membrane-based separation processes enhances the efficiency of catalytic and electrochemical reactions employed in these conversions (Badreldin and Li 2025). Furthermore, the coupling of innovative membrane materials like graphene oxide and MXene membranes with catalytic systems could optimize CO_2 conversion processes, reducing energy consumption and enhancing scalability (Iravani et al. 2024). The approach of transforming CO_2 from a pollutant into a valuable resource aligns with circular economy principles, providing a pathway to mitigate emissions while driving industrial innovation (Alli et al. 2024). The effective conversion of CO_2 to fuels and chemicals using renewable energy can be achieved by utilizing water electrolysis-based-green H_2 produced via the application of wind or solar power (Zheng et al. 2016; Li et al. 2018; Saleh and Hassan 2023; Boretti 2024) or biohydrogen via fermentation of organic biomass (Ahmed et al. 2021; Francisco López et al. 2024; Zhang et al. 2024a). Many nanoparticles participate in the reactions of carbon dioxide either on chemical or photochemical methods and others to produce products of high economic value (Alli et al. 2024). Among these nanomaterials, Fe, Cu, Ni, Ag, Co, Zn, Au NPs and Pd are very useful in this reaction (Posada-Pérez et al. 2023). Activation of CO_2 bonds during a chemical reaction is depending on the nature of nanomaterials regarding construction and the nature of capping agents, where the metallic sites must be in direct contact or available to reactants (Otto et al. 2015). The porosity of the prepared nanoparticles plays an important role to control the efficiency and selectivity of the catalysts besides their shapes, sizes, and dispersion due to easy diffusion of reactant to the active centers incorporated in the catalysts (Posada-Pérez et al. 2023). Significant attempts have also been devoted to prevent the agglomeration of nanoparticles and sustain their catalytic activity by developing hybrid composites in which silica, carbon, or polystyrene act as chemically compatible support on which desired metal NPs are deposited (Li et al. 2016a, b).

CO_2 conversion into chemicals

Valorization of CO_2 into valued products lays under the CCU, which mitigates the atmospheric CO_2 levels by its capturing and repurposing, thereby providing a sustainable carbon source for diverse industrial applications. This method corresponds with the tenets of a circular economy, wherein waste is reduced and resources are perpetually recycled (Maselli et al. 2024). CO_2 can be valorized via the application of renewable energy into chemicals, such as dimethyl ether (DME), acetic acid, formic acid, urea, in addition to C-neutral sustainable fuels for example syngas, methanol, Fischer–Tropsch synthesized jet, gasoline, diesel fuels, etc. (Goren et al. 2024).

$$(2n+1)H_2 + nCO_2 \rightarrow C_nH_{2n+2} + nH_2O$$

Conversion of CO_2 to methanol

Methanol ranks among the top ten industrial chemicals (Azharia et al. 2022), with annual global production surpassing 98 million tons (Tabibian and Sharifzadeh 2023). China is the top producer, contributing by approximately 50% of the global production, while Europe contributes by approximately 3% (Guil-López et al. 2019). The hydrogenation of CO_2 to methanol, utilizing hydrogen produced from renewable energy (Pratschner et al. 2023), algal and waste biomass (Fasihi and Breyer 2024), or during off-peak hours (Hillestad 2023), presents a viable method for recycling CO_2 and mitigating GHG emissions. Methanol is an attractive fuel owing to its elevated energy density and transport

convenience (Verhelst et al. 2019). It can be utilized directly as fuel, mixed with traditional fuels, and it can also function as a multifaceted liquid energy carrier (Parris et al. 2024). Methanol is essential in the synthesis of numerous compounds, such as formaldehyde (HCHO), ethylene, propylene, dimethyl ether (DME), and acetic acid (AC), and it holds promise for use in fuel cells, rendering it significant in both the energy and chemical industries (Bertau et al. 2014; Zhang et al. 2021a, b; Pawelczyk et al. 2022). Methanol-based chemicals, for example; acetic acid, dimethyl ether, formaldehyde, methyl methacrylate, and methyl tert-butyl ether, olefins have different industrial applications; packaging, pharmaceuticals, electronics, automotive, paints, and construction (Fasihi and Breyer 2024). In transportation sector, methanol can be used directly as gasoline/methanol blend (Hanifuddin et al. 2023) or can be converted to gasoline (Sanz-Martínez et al. 2022). The new coming era of renewable or green methanol has the capacity to reduce the carbon footprint of the chemical sector while concurrently replacing fossil fuels imports with local CO_2 sources. Replacing fossil fuels-derived methanol with green methanol is estimated to reduce CO_2 emissions by as much as 95%, as its production primarily relies on biomass as a carbon source, green hydrogen, and renewable energy (Pratschner et al. 2023). By 2050, it is projected that the production cost of renewable methanol will decrease by 250$ to 630$ per metric ton, as it is attributed to reductions in renewable energy prices (Tabibian, and Sharifzadeh 2023).

Methanol is industrially produced at elevated pressures (5–10 MPa) and temperatures (200–270 °C) from synthesis gas ($CO/CO_2/H_2$) over heterogeneous catalysts based on the ternary $CuO/ZnO/Al_2O_3$ (Baltes et al. 2008; Balopi et al. 2019) or $Cu/ZnO/Al_2O_3$ systems (Liang et al. 2019; Ruland et al. 2020). ZnO is the crucial catalyst for enhancing the system's activity (Guil-López et al. 2019). Moreover, Austin et al. (2016) investigated the electronic structure of CO_2 adsorbed on the 55-atom bimetallic CuNi nanoparticles ($Cu_{12}Ni_{43}$ and core–shell $Cu_{42}Ni_{13}$) as catalyst by Density functional theory (DFT). They found that the presence of Ni on the surface of CuNi-NPs is key for both adsorbing and activating the CO_2 molecule via a charge transfer from the Ni-NPs to the CO_2 molecule, where the d-orbital of Ni that locates on the surface plays a pivotal role in this process. Carenco et al. (2015) reported that the evolution of bimetallic Ni-Co NPs (Ni:Co 1) that was promoted with trioctylphosphine in the reaction of H_2 and CO_2. They found that P-atom, from the trioctylphosphine ligands, was well-dispersed (segregated) on the NPs, producing phosphorous oxide P (+ V) moieties (phosphate). The products were mainly 70%–CO, 20%–HCHO and 10%–CH_3OH at 350 °C.

Although modeling studies and isotopic labeling experiments suggest that CO_2 is the primary source of methanol (Chinchen et al. 1987), CO is still required in the feed. This need arises because CO is converted to CO_2, which helps in removing the unwanted water through the water–gas shift reaction (WGSR);

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$$

The WGSR is crucial for maintaining catalyst activity and reaction efficiency by preventing water accumulation, which can deactivate the catalyst over time (Studt et al. 2015). The $Cu/ZnO/Al_2O_3$ system is preferred for methanol synthesis due to its high catalytic efficiency, cost-effectiveness, and durability under reaction conditions, making it ideal for large-scale industrial applications (Pacchioni 2024). However, other catalysts have been applied in CO_2 hydrogenation to methanol, for example; Indium (Yao et al. 2019) and indium oxide In_2O_3 (Lawes et al. 2024), which are reported to express efficient selectivity and enhanced activity. Besides, the unsupported bimetallic Pd-In nanoparticles (NPs) have been also reported for its high selectivity (García-Trenco et al. 2018). Witoon et al. (2018a) studied the effect of adding graphene oxide (GO) at different loadings to a $CuO–ZnO–ZrO_2$ catalyst and found that the GO nanosheets could act as a bridge between the mixed metal oxides. This promoted H_2 spillover from the copper surface to the carbon species adsorbed on the isolated metal oxide particles, resulting in a remarkable enhancement of both methanol selectivity and production rate (Fig. 2a). However, they also found that adding GO in amounts higher than 2.5 wt% led to a significant increase in CuO particle size, which caused a lower methanol production rate. In a related study, Tada et al. (2018) synthesized various $Cu-ZrO_2$ catalysts, including $Cu/a-ZrO_2$ (amorphous ZrO_2), $Cu/m-ZrO_2$ (monoclinic ZrO_2), $Cu/a-ZrO_2$/KIT-6, and $Cu/t-ZrO_2$/KIT-6 (tetragonal ZrO_2), via a straightforward impregnation method to examine how different ZrO_2 phases affect CO_2 hydrogenation to methanol. High dispersion of Cu species combined with weaker methanol adsorption contributed to enhanced catalytic activity and methanol selectivity in CO_2 hydrogenation (Fig. 2b). Methanol vapor sorption analysis further indicated that α-ZrO_2 exhibited weaker methanol adsorption compared to m-ZrO_2, which positively influenced reaction performance. Ali et al. (2022) explored how variables in solution combustion synthesis (SCS) impact the efficiency of copper-based catalysts for CO_2 hydrogenation to methanol. They synthesized a catalyst with 30 wt% CuO and 50 wt% ZnO on an Al_2O_3 support, using different glycine-to-nitrate (G/N) ratios between 0.1 and 1.23. Additionally, they examined how calcination and activation temperatures influence catalytic performance. The catalyst prepared at a G/N ratio of 0.206, calcined in air at 400 °C and activated in hydrogen at 350 °C, showed a marked enhancement in CO_2 hydrogenation performance. This improved activity was attributed to the

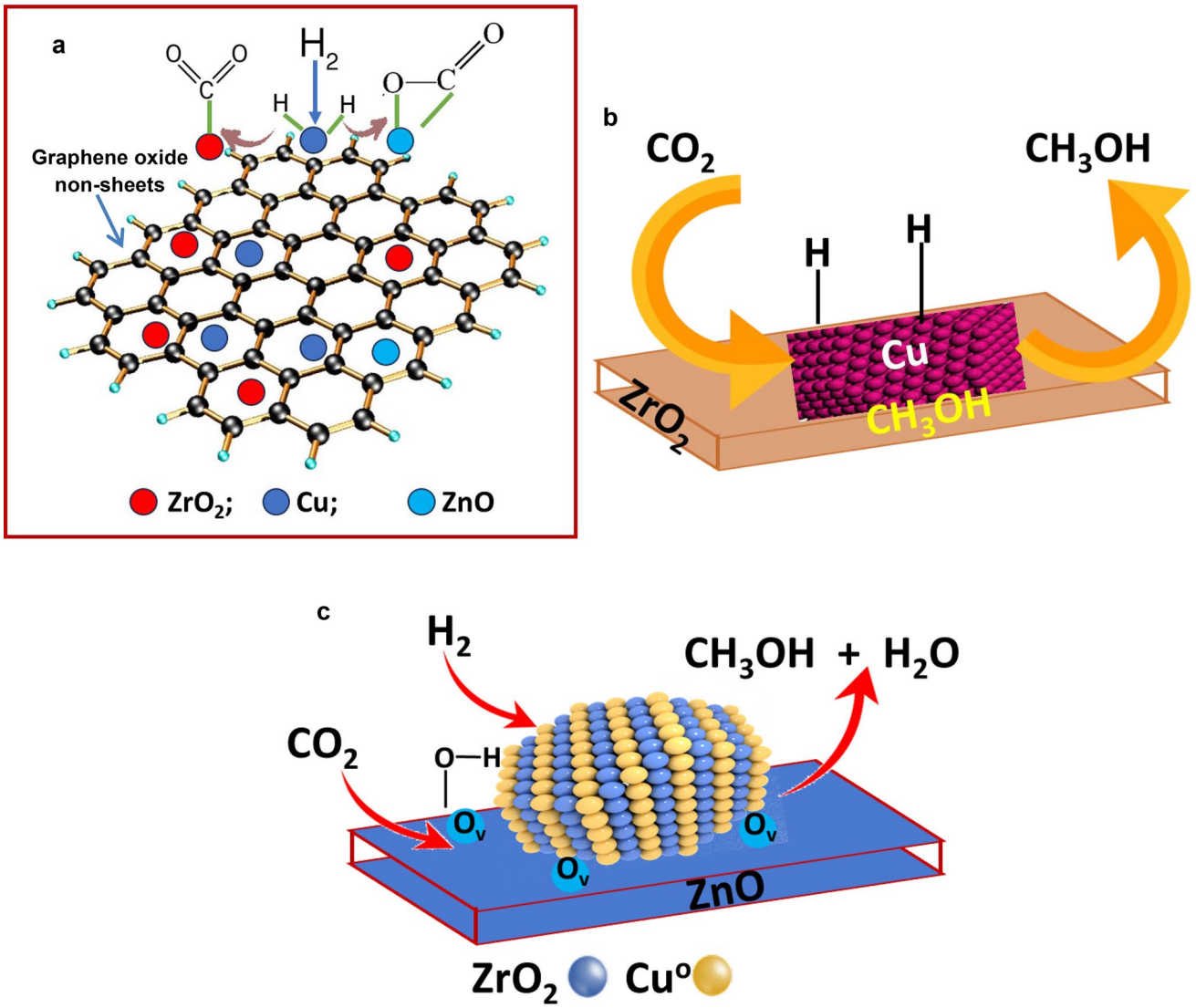

Fig. 2 GO-nanosheet as a conduit facilitating H_2 overflow from the Cu-surface to that of other metal oxides **a**, schematic diagram for CO_2 conversion to methanol on Cu/Zr-KIT-6 catalyst **b** and Cu–ZnO–ZrO_2 catalyst **c**

synergistic effect between finely dispersed CuO NPs and an abundance of copper phases. The catalyst exhibited its highest activity under conditions of 300 °C, 85 bar pressure, and a gas hourly space velocity (GHSV) of 7000 h^{-1}, yielding CO_2 conversion of 30%, CO selectivity of 38.6%, and methanol selectivity of 61.4%. The corresponding methanol and CO yields were 0.52 gMeOH/g-cat·h and 0.33 gCO/g-cat·h, respectively. Sun et al. (2023) investigated the effect of varying the molar ratios of ZrO_2 on the performance of Cu–ZnO catalysts in CO_2 hydrogenation to methanol, focusing on optimizing the distribution of Cu^0 and Cu^+ species. Their results revealed a volcano-shaped trend in catalyst performance, where the ratio of $Cu^+/(Cu^+ + Cu^0)$ varied with different ZrO_2 concentrations. Among the tested ratios, the $CuZn_{10}Zr$ catalyst (with a 10% molar ratio of ZrO_2) exhibited the highest Cu^+ content, which is critical for promoting CO_2 activation and methanol selectivity. Consequently, this catalyst achieved the maximum space–time yield of methanol at 0.65 gMeOH/(gcat·hr), under conditions of 220 °C and 3 MPa (Fig. 2c).

Carbon dioxide methanation

CO_2 methanation was first reported by the French chemists Paul Sabatier and Jean-Baptiste Senderens in 1897 (Che 2013), via the suggestion of Sabatier reaction;

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \Delta H_{298K} = -164.747\ \text{kJ/mol}$$

As indicated by this equation, the methanation of carbon dioxide with hydrogen is an exothermic reaction. This

exothermic nature of the reaction presents both opportunities and challenges. While it Sabatier reaction enables the efficient conversion of CO_2 (Alper and Orhan 2017), achieving high efficiency in industrial applications requires overcoming obstacles such as catalyst deactivation at high temperatures and the need for optimized reaction conditions to maximize yield (Sun and Simakov 2017).

This reaction, employing inexpensive and stable catalysts, and offers a promising method to store renewable energy, as it enables the transformation of surplus renewable energy into methane, a valuable fuel. It also provides an effective way to convert biogas into biomethane and to transform CO_2 into chemical feedstocks and fuels, making it a key process for both energy storage and carbon capture and utilization (CCU) (Tripodi et al. 2020). Furthermore, the application of the Sabatier reaction extends beyond terrestrial uses. Research has been conducted on its potential for reclaiming oxygen aboard the international space station (ISS), where exhaled CO_2 from astronauts can be converted into precious water and fuel for life-support systems, contributing to a sustainable environment in space (Murdoch et al. 2012).

In recent years, much work has been done to develop thermally stable catalysts with high activity at low temperatures. Several researchers have used to catalyze carbon dioxide methanation Ni/SBA-15, Ni/Ce/SBA-15, Ni/MCM-41, Ni/Ce/MCM-41 (Bacariza et al. 2018), Ni/Al_2O_3-ZrO_2-TiO_2 (Mebrahtu et al. 2018), Ni/Mg/La/Al (Wierzbicki et al. 2018), La-Ni/Mg–Al (Zhang et al. 2018a, b), FeO, Fe_3O_4, γ-Fe_2O_3 (Kirchner et al. 2018), NiRu/CaO-Al_2O_3 (Liu et al. 2018), Zr-, Ce-, and La-Co_3O_4 (Zhou et al. 2018), NiO/CeO_2 (Cárdenas-Arenas et al. 2021), Ni/Y_2O_3 (Lee et al. 2021), Ru/TiO_2 (Zhou et al. 2022), Ni/Mg–Al (Han et al. 2022), Ni/ ZrO_2-Al_2O_3 (Fu et al. 2023), Ni–Fe (Yan et al. 2024), NiRu (Merkouri et al. 2023), and Ni/Co_3O_4 (Chitturi et al. 2025). Li et al. (2018) screened different supports including ZrO_2, Al_2O_3, SiO_2, SiC, TiO_2 and activated carbon (AC) loaded with 10 wt.% Co for carbon dioxide methanation. The Co/ZrO_2 catalyst expressed both the highest stability and CH_4 yield. Cui et al. (2021) developed a catalyst composed of Co-MnO heterostructured nanoparticles embedded within porous graphitic carbon (Co/MnO@PGC). Their study demonstrated that this catalyst effectively converted CO_2 to methane at 160 °C, achieving a high methane selectivity of over 99%. Furthermore, the catalyst exhibited a turnover frequency of 0.26 s^{-1} for methane production, indicating its efficiency in promoting CO_2 hydrogenation to methane. Gregory et al. (2024) studied the hydrogenation of CO_2 to methane using a 20 wt.% Ir/TiO_2 catalytic coating in a tubular dielectric barrier discharge (DBD) reactor. The 1.2 µm thick Ir/TiO_2 coating was applied to the inner wall of a quartz tube using a combustion-evaporation method, utilizing a mixture of a titanium precursor and a colloidal suspension of 2 nm Ir nanoparticles (Fig. 3). The presence of the catalyst significantly enhanced CH_4 conversion, which was by 1.5 times than that occurred in an empty reactor tube. The highest CO_2 conversion rate observed was 2.1 µmol/sec, with a fuel production efficiency of 3.5%.

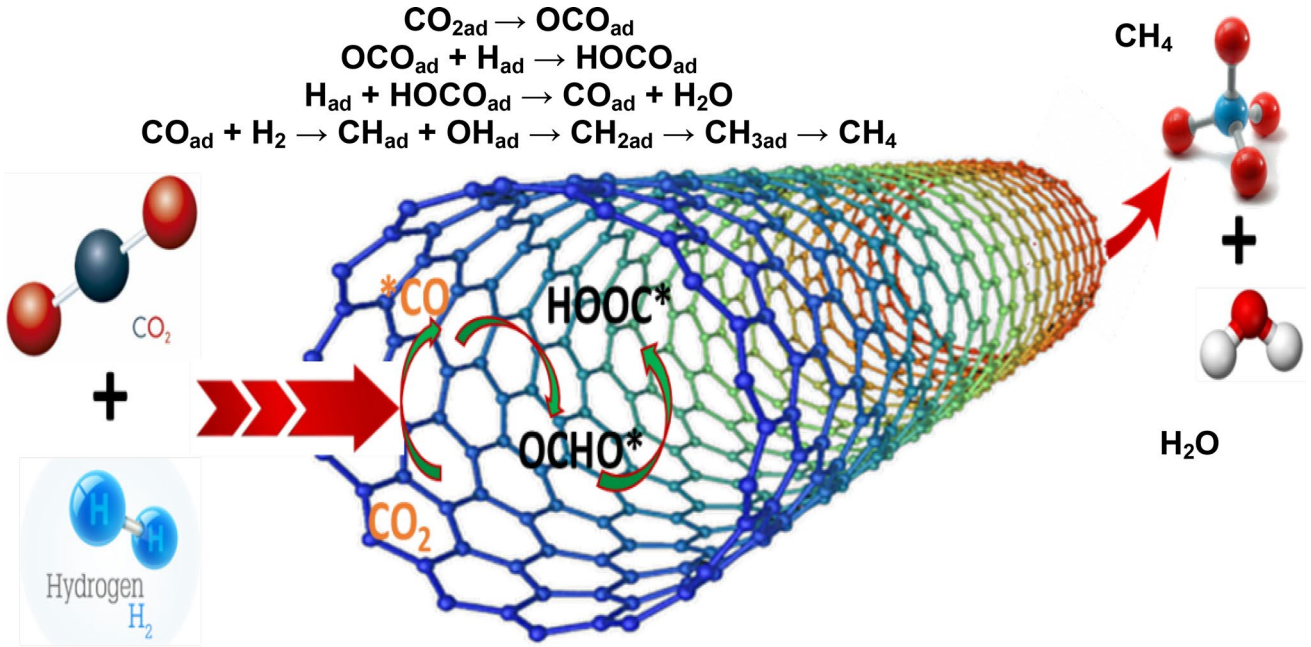

Fig. 3 CO_2 methanation over a 20 wt.% Ir/TiO_2 catalyst

CO_2 conversion to dimethyl ether

The transformation of carbon dioxide and hydrogen into small hydrogenated molecules such as dimethyl ether (DME) is very promising and gained significant consideration, as it can as an intermediate for the production of different valued products, for example olefin, gasoline, and aromatics and it can be used also as an alternative fuel that can be stored and transported using the existing infrastructure (Catizzone et al. 2018). DME is very motivating because it can be applied in a diesel engine due to its height cetane-number (Agarwal et al. 2023). The DME molecule does not have a carbon–carbon bond, thus, its combustion does not release any particulate emission and can be considered as a clean fuel (Soltic et al. 2024). In addition, DME can be used as an effective hydrogen carrier for fuel cell implementation (Schühle et al. 2023). More importantly, DME can be prepared from recycled CO_2 using renewable energy which is an effective way to obtain a sustainable carbon cycle (Fig. 4) (Liu and Liu 2022).

DME can be produced via a two-step or direct pathway (Fig. 4), where CO_2 is first hydrogenated to methanol, which is subsequently dehydrated to form DME over solid acid catalysts such as γ-alumina or zeolites (Liu and Liu 2022);

Hydrogenation of carbon dioxide

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \Delta H_{298K} = -49.4\ \mathrm{kJ/mol}$$

Methanol dehydration to dimethyl ether

$$2CH_3OH \leftrightarrow CH_3OCH_3 \Delta H_{298K} = -24.0\ \mathrm{kJ/mol}$$

The integration of these catalytic functions in bifunctional catalysts enables direct conversion, enhancing process efficiency and reducing energy requirements. Hybrid catalysts combining $Cu/ZnO/Al_2O_3$ for methanol synthesis with acidic zeolites like ZSM-5 have shown promising results in improving DME yield while maintaining high CO_2 conversion rates (Tariq et al. 2021). The ternary $CuO–ZnO–ZrO_2$ catalyst (Arena et al. 2007) has been reported to be the most efficient catalyst for the synthesis of methanol from CO_2 hydrogenation due to its high activity and stability compared a commercial $CuO–ZnO–Al_2O_3$/HZSM-5 (Zhang et al. 2014), which is an apparent choice to be used in the single-step synthesis of DME from CO_2. Several catalysts are used in the conversion of CO_2 to DME. The $CuO–ZnO–ZrO_2$ (CZZr) supported on SAPO-11 (S-11) expressed high stability and over 80% selectivity towards DME, upon the direct conversion of syngas and CO_2 into DME, with a negligible synthesis of paraffin (Sánchez-Contador et al. 2018). Ateka et al. (2018) reported a high syngas and CO_2 conversion, DME yield and selectivity that is greater than 94%, with a concomitant moderate carbon

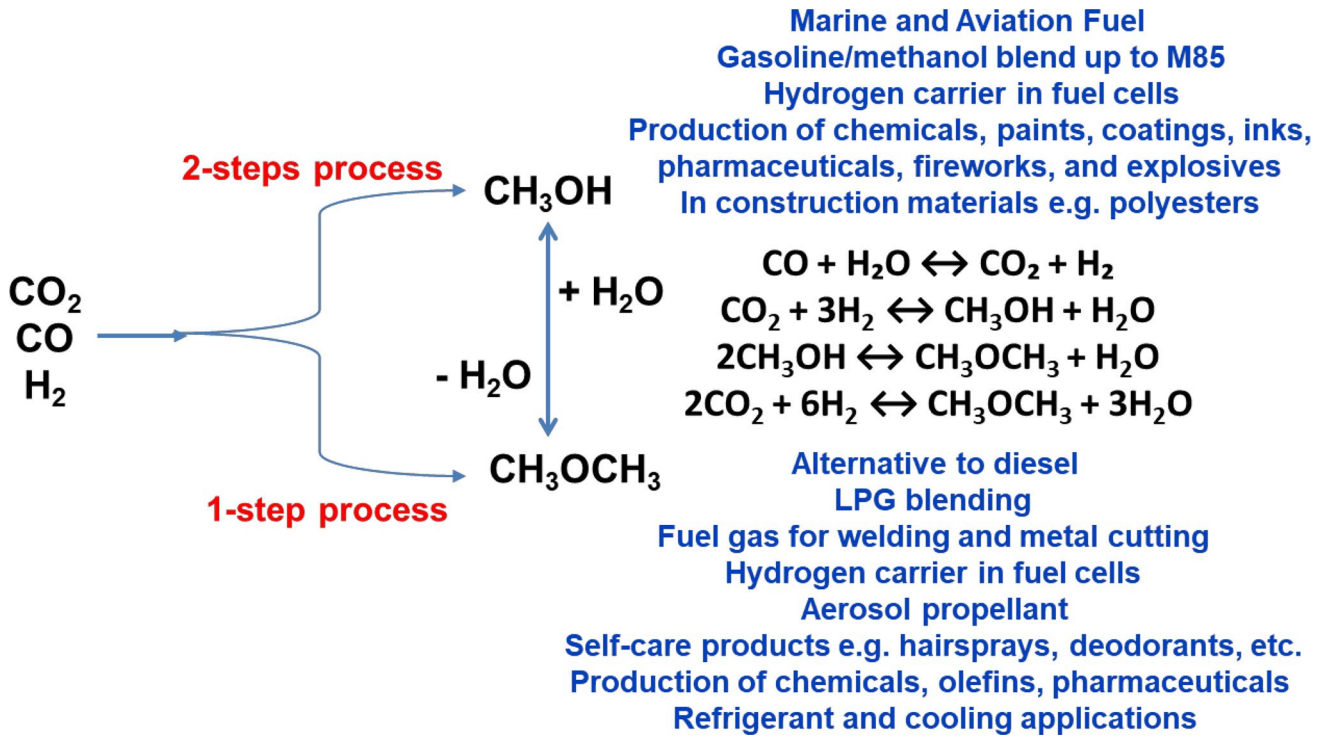

Fig. 4 CO_2 conversion into methanol and dimethyl ether and their possible applications

deposition and catalyst deactivation, upon the application of metallic/acid bi-functional catalyst CuO–ZnO–MnO/SAPO-18 (CZMn-S18). The ferrite particles size found to be critical in the catalytic behavior and stability of CuZnZr-FER during the direct conversion of CO_2 into DME (Bonura et al. 2018). Witoon et al. (2018b) examined the catalytic activity of CuO–ZnO–ZrO_2-WOx/ZrO_2 in direct conversion of CO_2 into DME. The calcination temperature in catalyst preparation has been also reported to be critical, whereas, WOx/ZrO_2 calcinated at 900 °C expressed the highest stability, CO_2 conversion, DME yield and selectivity. The PdZn/TiO_2—ZSM-5 for example showed efficient conversion and stability, whereas, CO_2 can be converted into adsorbed carbonate and then hydrogenated into bicarbonate and methoxy CH_3O^* on Pd and PdZn. Yet, Pd can induce the C–O dissociation to generate methane, whereas PdZn can stabilize the formed CH_3O* to produce methanol on TiO_2. Moreover, the solid acid ZSM-5 catalyzes the dehydration of the two formed CH_3O* molecules to produce DME (Bahruji et al. 2022). Li et al. (2023a) developed a silica-supported copper catalyst, Cu/Ga-SiO_2-Me, by modulating gallium species and incorporating hydrophobic methyl groups to enhance DME selectivity and catalyst durability. Characterization showed that gallium species electronically influenced the Cu nanoparticles, promoting the formation of $Cu^{\delta+}$ species, which reduced CO selectivity by minimizing the reverse water–gas shift reaction. The methyl groups facilitated the rapid removal of water from the catalyst surface, preventing Cu sintering and boosting catalytic performance. The Cu/Ga-SiO_2-20Me catalyst achieved 9.7% CO_2 conversion, with DME and methanol selectivities of 59.3% and 28.4%, respectively, and a CO selectivity of just 11.3%. This approach offers valuable insights for improving industrial catalysts. Bonura et al. (2023) developed 3D-printed CuO–ZnO–ZrO_2/zeolite hybrid catalysts for the direct hydrogenation of CO_2 to DME using a robocasting technique to extrude an ink-like catalytic paste. This method allows precise control over the catalyst's structure, surface, and geometry, improving heat and mass management compared to traditional powdered catalysts. The catalyst's performance depends on the interaction between the metal-oxide and acidic phases. Additionally, the accessibility of CO_2 activation and methanol dehydration sites on the hybrid catalyst significantly influences catalytic activity, with turnover frequencies for CO_2 conversion and DME formation highlighting the importance of exposing chemisorption sites to enhance reactivity. Nintao et al. (2023) investigated the effect of microwave drying on alumina supports and Cu/Al_2O_3 catalysts. Microwave drying at 600 and 1000 W reduced drying time by 86% and 92%, respectively, compared to hot air drying. This method improved the distribution of alumina particles, increasing surface area and pore volume, whereas hot air drying caused particle aggregation. The Cu/Al_2O_3 catalyst dried at 1000 W (Cu/Al_2O_3-MW1000) exhibited the highest copper distribution, surface area (229.5 m^2/g), pore volume (0.39 m^3/g), and acidic sites (1.25 mmol NH_3/g Cu), resulting in superior CO_2 conversion (30.67%), DME selectivity (9.99%), and DME space–time yield (156.5 gDME/kgcat·h) at 260 °C. The catalyst showed excellent stability over 24 h.

CO_2 conversion to acetic acid

The sequestration of CO_2 and its subsequent chemical conversion into a useful compound such as acetic acid (CH_3COOH), which is extensively utilized in the manufacture of polymers, textiles, and food preservatives, is a burgeoning field of inquiry within green chemistry and sustainable chemical methodologies. Acetic acid is presently manufactured industrially by the BP/Monsanto process, utilizing a rhodium or iridium catalyst for the methanol carbonylation (Rabie et al. 2017).

$$CO_2 + CH_4 \leftrightarrow CH_3COOH \Delta H_{298K} = +8.62\ \mathrm{kJ/mol}$$

However, the process of direct synthesis of acetic acid from carbon dioxide and methane is challenging due to the thermodynamic limitations, and it needs to activate both methane and carbon dioxide simultaneously (Zhao et al. 2016). Recently, heterogeneous catalysts approach mostly has focused on how to activate the two molecules simultaneously experimentally and theoretically (Zan et al. 2024).

Wu et al. (2013) reported a high selectivity conversion of carbon dioxide and CH_4 to acetic acid using the bifunctional catalyst Zn supported on zeolite HZSM-5 at low range of temperatures 250–500 °C (Fig. 5a). The possible illucidated mechnism is the formation of Zn–CH_3 group via activation of methane over Zn followed by the insertion of CO_2 in the Zn–CH_3 bond, producing –Zn–$OOCCH_3$. The resulted acetic acid was formed through proton transfer and the Brønsted acid sites are represented as the necessary role for this transformation. Montejo-Valencia et al. (2017) used the density functional theory (DFT) to elucidate the mechanization of co-conversion of CO_2 and CH_4 to acetic acid by using exchanged MFI zeolite with different metals such as Cu, Mn, Zn, Co, Mg, and Be (Fig. 5b), where the CO_2 activation is helping the formation of carbonate species at the cation sites. Montejo-Valencia et al. (2017) elucidated that the most significant reaction barrier in the mechanism is found to be the dissociation of CH_4, which occurs concurrently with a charge transfer between CH_4 and the metal cation. The insertion of CO_2 exhibits a low energy barrier, while the protonation of acetate species occurs spontaneously. Dispersion interactions primarily contribute to the adsorption energies of CH_4, while their contribution to the energies of reaction in subsequent steps of the mechanism is nearly negligible. Moreover, the

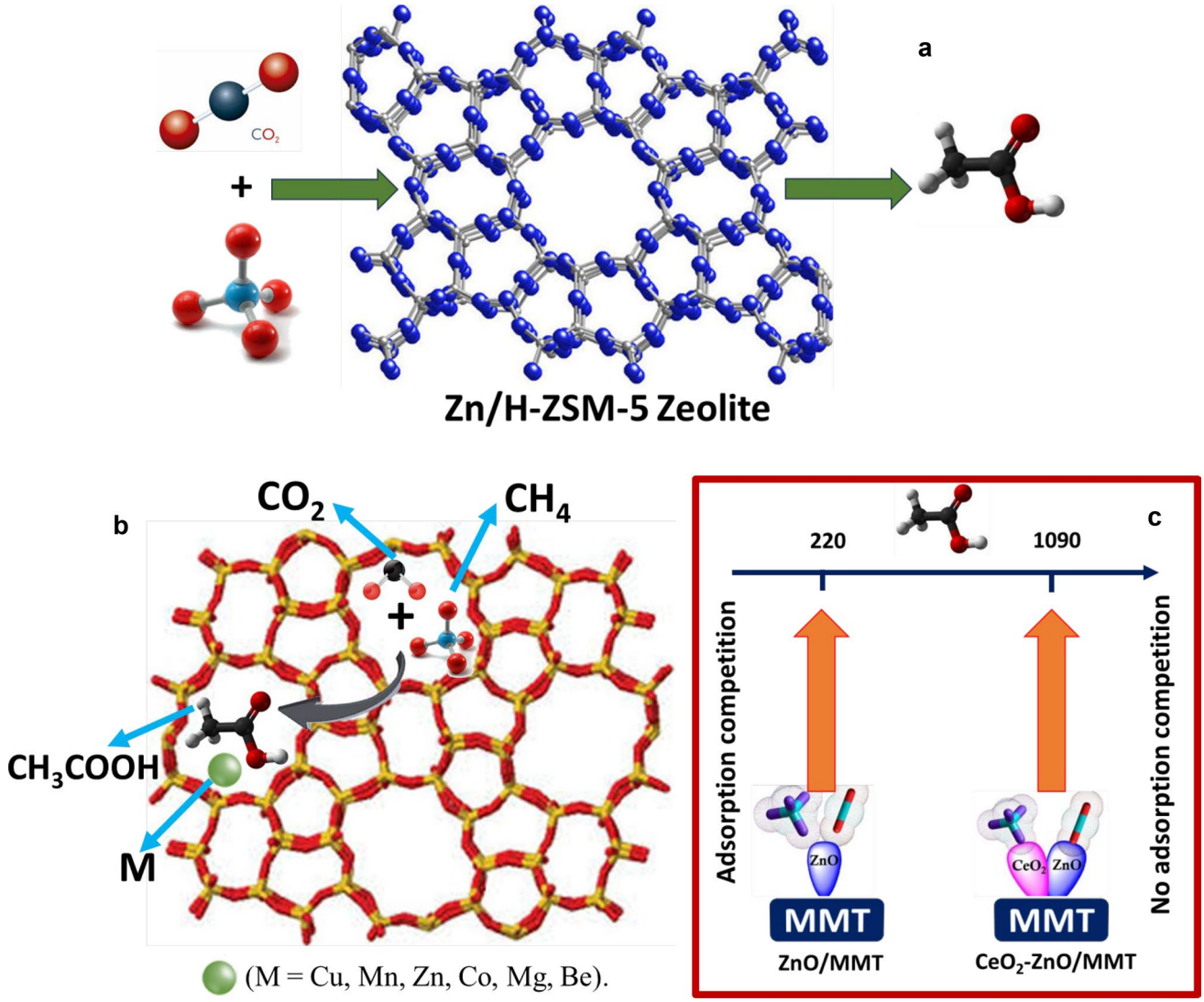

Fig. 5 **a** The acetic acid formation from CH_4 and CO_2 over bifunctional catalyst Zn supported on zeolite HZSM-5; **b** MFI atoms cluster used for the density functional theory (DFT) calculations of metal-MFI. The green colour is the metal atom (M = Cu, Mn, Zn, Co, Mg, Be); **c** a graphical figure for the co-activation of CO_2 and CH_4 over single and coupled metal oxides supported montmorillonite

co-adsorption of water may facilitate the desorption of acetic acid. Shavi et al. (2018) supported two unlike metal oxides on zeolite montmorillonite (MMT) catalysts to act as dual active sites on the catalyst surface and to overcome the adsorption limitation of the reactant gases (Fig. 5c). CeO_2–ZnO/MMT, MnO_2–ZnO/MMT, and CeO_2-MnO_2/MMT catalysts were prepared and examined. The formation of Zn–COOH was much faster than that of Ce-COOH and denoted as the rate determining step. Moreover, the CeO_2 preferentially adsorb CO_2, while the ZnO preferentially adsorb CH_4, thus, CeO_2–ZnO/MMT overcomes the adsorption competition. The DFT studies demonstrated that the synthesis of acetic acid is significantly promoted on the ZnO catalyst, and facilitated by the more facile migration of adsorbed CO_2 from CeO_2 to the ZnO surface.

CO_2 conversion to other valued chemicals

Srivastava et al. (2005) have reported the synthesis of alkyl/aryl carbamates through a three-component one-pot reaction between alkyl/aryl amines, CO_2, and n-butyl bromide over adenine-functionalized Ti-SBA-15 material. Here nitrogen-rich basic sites of adenine activate the CO_2 molecules, whereas Ti^{4+} of the Ti-SBA-15 inorganic support activates the amines to make the carbamate synthesis successful.

Seki et al. (2009) have employed MCM-41/HMS-type ordered mesoporous silica materials as catalysts for the direct fixation of CO_2 to N,N'-dimethyl ethylene diamine to obtain 1,3-dimethyl-2-imidazolidinone under supercritical CO_2 conditions.

Metal–organic frameworks (MOFs) are a group of highly crystalline porous materials the surfaces of which can be utilized for the stabilization and dispersion of nanoparticles (Gu et al. 2011). MOFs consist of metal ions centers connected by organic linkers, and have exceptionally high BET surface areas, uniform pore size distribution, and chemical diversity (Wen et al. 2014). Toyao et al. (2015) have stabilized metallic nanoparticles at the surface of a zeolitic imidazolate framework (ZIF) for different CO_2 fixation reactions, in which the presence of an imidazolate moiety could activate the CO_2 molecules as well as stabilizing the metallic NPs. The produced catalyst enhanced the reaction between CO_2 and epoxides at 80 °C and 0.6 MPa, producing cyclic carbonates. Moreover, CO_2 can be polymerized with epoxides via the application of metal-complex-catalysts into polycarbonates, which are resilient plastics utilized in building, medical devices, and electronics (Alli et al. 2024). CO_2 can also be valorized into graphene with various industrial applications (Bafqi et al. 2024).

Ballivet-Tkatchenko et al. (2011) reported that a Sn-containing mesoporous silica material (Sn-SBA-15) has shown good reactivity for the synthesis of dimethyl carbonate (DMC) in the coupling of CO_2 and methanol under high CO_2 pressure, with turnover numbers of 6.0 at 150 °C and 20 MPa. Although the synthesis of DMC from CO_2 can proceed under much lower CO_2 pressure in the presence of supported metallic nanoparticles, this post-synthetic functionalization route for grafting of Sn^{IV} over highly ordered 2D-hexagonal mesoporous silica has its advantage of utilizing surface acidity of the catalyst.

Cui et al. (2015) reported for the first time that the incorporation of tiny AgNPs (1–3 nm) in sulfonated hierarchically porous resin leads to the formation of cyclic carbonates molecules in the presence of CO_2. It was found that the AgNPs/sulfonated hierarchically porous resin was an easily recyclable catalyst for α-alkylidene cyclic carbonates synthesis by carboxylative cyclization of propargyl alcohols with CO_2 at room temperature. The Ag NPs activate the propargyl alcohol triple bond in the presence of a base (1,8-diazabicyclo[5.4.0]undec-7-ene) that react with CO_2, forming intermediate (carbonate moieties) that undergo ring closing to α-alkylidene molecules. This work has been strengthened by Zhao et al. (2017), the authors prepared Cd-metal organic framework as a catalyst for the carboxylative cyclization of propargyl alcohols with CO_2 which gave cyclic compound similar to that obtained by Cui et al. (2015).

Li et al. (2016a, b) demonstrated a new strategy to enhance catalytic activity and selectivity of Cu NPs for the reduction of CO_2. They prepared highly dispersed Cu NPs deposited on N_2-rich g-C_3N_4 for the reduction of CO_2 to ethylene molecule. The catalyst showed ethylene selectivity of 79%. The N_2-rich functionalities act as an adsorption site for CO_2, which facilitates the hydrogenation and the formation of C–C bond on nano metallic sites of Cu to C_2H_4.

CO_2 can be also valorized into formic acid (Ghazi et al. 2024), which has different applications in agricultural and industrial sectors (Thijs et al. 2022).

$$CO_2 + 2H^+ + 2e^- \rightarrow HCOOHCO_2 + 2H^+ + 2e^- \rightarrow HCOOH$$

Syngas from CO_2 and methane

It is known that carbon dioxide is converted into high-energy chemicals by the type of catalysts used. Among these products is the renewable syngas because it represents an important intermediary to several industries such as methanol production and many other chemicals (Mohanty et al. 2021). Synthesis gas is applied as a reactant to synthesis a long-chain hydrocarbons using the Fischer–Tropsch reaction (Hannula et al. 2020). The syngas production route is most prevalent through steam reforming of methane (SRM) however, this process requires high temperatures up to 900 °C and very large amounts of steam (Zhang et al. 2021a, b).

$$SRMCH_4 + H_2O \rightarrow CO + 3H_2 \Delta H_{298K} = +206\ \text{kJ/mol},\ \Delta G_{298k} = +142\ \text{kJ/mol}$$

Dry reforming of methane (DRM) is an endothermic reaction and requires high temperatures, typically in the range of 700–1000 °C, as well as a catalyst, such as nickel-based or noble metal-based catalysts, to efficiently proceed.

$$DRMCH_4 + CO_2 \rightarrow 2CO + 2H_2 \Delta H_{298K} = +247\ \text{kJ/mol},\ \Delta G_{298k} = +170\ \text{kJ/mol}$$

The DRM is very considerable from the environmental point of view, because CH_4 and CO_2 are the main contributors of the GHG (Bauduin et al. 2024), and their utilization would reduce their effects on global warming (Landa et al. 2023). Moreover, it can be applied for lignocellulosic wastes management, via the pyrolysis of biomass, producing a large amount of CH_4 and CO_2, which can be further used in syngas production (Frantzi and Zabaniotou 2021). Not only that, but the biomass anaerobic digestion produces biogas, whereas its main components are CO_2 and CH_4, which can be also further valorized into syngas (Enebe et al. 2023). Table 2 summarizes the advantages and disadvantages of DRM and SRM.

The most studied catalyst for DRM with CO_2 has supported nickel materials. However, the Ni supported catalysts incline to coke formation on catalyst surface, this behavior leading to catalyst deactivation or blocking the tubes inside the reactor. Therefore, the researchers resort to the use of some noble metals such as Ru and Rh because it has more

Table 2 Steam verses dry reforming of methane

Steam reforming of methane	Dry reforming of methane
• It is a well-established technology • Generates an elevated H_2/CO ratio (~ 3:1) • It is optimal for H_2 production • It can be integrated in manufacturing of ammonia, in H_2-fuel cells, methanol production, hydrotreatment in refineries • It consumes huge amount of steam, so it has high water footprint • Lower energy consumption as it operates at relatively lower temperature ranges 700–900 °C • It is an energy intensive endothermic reaction • Relatively lower C-deposition on catalyst • High emitted CO_2 as a by-product	• It is considered as CCU method as the main reactants are CH_4, CO_2 • Generates a relatively lower H_2/CO ratio (~ 1:1) • It is optimal to be integrated with Fischer–Tropsch process • No water requirement, so relatively low water footprint • Higher energy consumption as it operates at relatively higher temperature ranges 700–1000 °C • It is a relatively higher energy intensive endothermic reaction • Relatively higher C-deposition on catalyst, leading to deactivation, leading to increased maintenance costs • Catalysts exhibit increased vulnerability to sintering and deterioration at elevated temperatures

catalytic activity as well as because it leads to reduce the cock deposition, but their cost and lower availability are barring to be alternative to supported nickel materials (Usman et al. 2015; Hussien and Polychronopoulou 2022). Considerable researches have been also reported in dry reforming of methane with CO_2 such as; Ru/ZrO_2 (Jakobsen et al. 2010), nickel hydroxyapatite-based catalyst (Ni/Ca-HA1_S) (de Vasconcelos et al. 2018), $LaNiO_3$/chitosan (Oliveira et al. 2018), $La_{0.6}Sr_{0.4}CrO_3$ and $Ce_{0.9}Gd_{0.1}O_2$ (Sarno et al. 2018), hydroxyapatite supported bimetallic Ni-Co catalyst (Phan et al. 2018), Ir/Ni-Co/Al_2O_3- ZrO_2 (Fakeeha et al. 2018), Co–CeO_2 (Zhang et al. 2018a, b), bimetallic Ni-Co catalysts (Guo et al. 2024),

The DRM with CO_2 was studied by a novel catalyst Ni-SiO_2@CeO_2 with nickel nanoparticles in the midst between silicon oxide and cerium oxide layers. The high activity of Ni-SiO_2@CeO_2 was attributed to the high dispersion of Ni nanoparticles on SiO_2@CeO_2 support. In addition to the core–shell framework prevented the nickel sintering which led to the cock formation resistance (Das et al. 2018). Park et al. (2018) designed cobalt supported on phosphorus-alumina catalyst for the DRM and CO_2. The efficient conversion was attributed to the good dispersion of Co, however CoP(x)Al catalysts expressed higher stability than CoAl catalyst. That was attributed to the development of inactive $CoAl_2O_4$, as a result of the occurrence of reaction between alumina and the oxidized CoO_x. Yet, $AlPO_4$ overwhelmed the development of $CoAl_2O_4$. Xin et al. (2018) succeeded to prepare bimetallic Ni-Co/SBA-15 catalysts using urea co-precipitation method and applied the prepared catalysts in the production process of syngas via DRM and CO_2. It was found that the small ratio of Co/Ni manifested a clear effect on coke and oxidation resistance. The Ni_9Co_1/SBA-15 catalyst expressed the best catalytic activity because of the high sintering resistance. Oni et al. (2023) studied the DRM with CO_2 using Co-$La_{1-x}Ca_xNiO_3$ perovskite-type oxides supported on ZrO_2. The most active catalyst was 2%Co-$La_{0.2}Ca_{0.8}NiO_3$-ZrO_2, which benefited from the synergistic interaction between Ni and Co in the perovskite lattice. This synergy enhanced the catalyst's performance, minimized carbon deposition, and demonstrated excellent stability, activity, and achieving the highest CO_2 and CH_4 conversions of 90% and 88%, respectively. Li et al. (2024) reported that the shape of Ni/Al_2O_3 expressed different efficacy in DRM and resistance against C-deposition. The wire shaped Ni/Al_2O_3-W nanostructure showed the highest conversion efficiency, catalyst stability, and lowest C-deposition. It exhibits robust metal-support interaction, a high surface dispersion of tiny Ni nanoparticles, and significant activation capability towards CO_2. The diffuse reflection infrared Fourier transform spectroscopy analysis clarified the essential function of OH* species in influencing an anti-coke efficacy and it interact with CH_x* intermediate species from CH_4 cracking, which also significantly influence the overall anti-coke efficacy of Ni/Al_2O_3-W catalysts. The encapsulating effect of the flower-shaped Al_2O_3 nanostructure led to an inadequate presence of metallic Ni active sites on the Ni/Al_2O_3-F surface, resulting in suboptimal initial catalytic activity. The limited CO_2 activation capability and the substantial particle size of metallic Ni on spherical shaped Ni/Al_2O_3-S resulted in significant filamentous carbon production following an extended DRM examination. Wang et al. (2024a) reported 0.6% Ir/CeO_{2-x} catalyst, demonstrating high conversion rates of CH_4 and CO_2, recorded approximately 72% and 82%, respectively, with a consistent CH_4 reaction rate of approximately 973 µmol CH_4/gcat/sec over duration of 100 h at 700 °C. That study emphasized the significance of the interfacial structure as an inherent active center that promotes CH_4 dissociation (the rate-determining phase) and the oxidation of CH_2* to CH_2O* without coke development, hence contributing to long-term stability. Hu et al. (2024) developed N-doped Ni-based bifunctional nanomaterials (Ni-Co/NC) derived from metal–organic frameworks (MOFs) to serve as both microwave absorbers and catalysts. The catalyst was employed in the DRM with CO_2 (Fig. 6), facilitating efficient syngas production through the microwave-enhanced DRM process. The N-doping found to exhibit a beneficial impact on the conversion rates of CH_4 and CO_2. That occurred through the facilitation of the development of a carbon protective layer and the prevention of the aggregation of active metals.

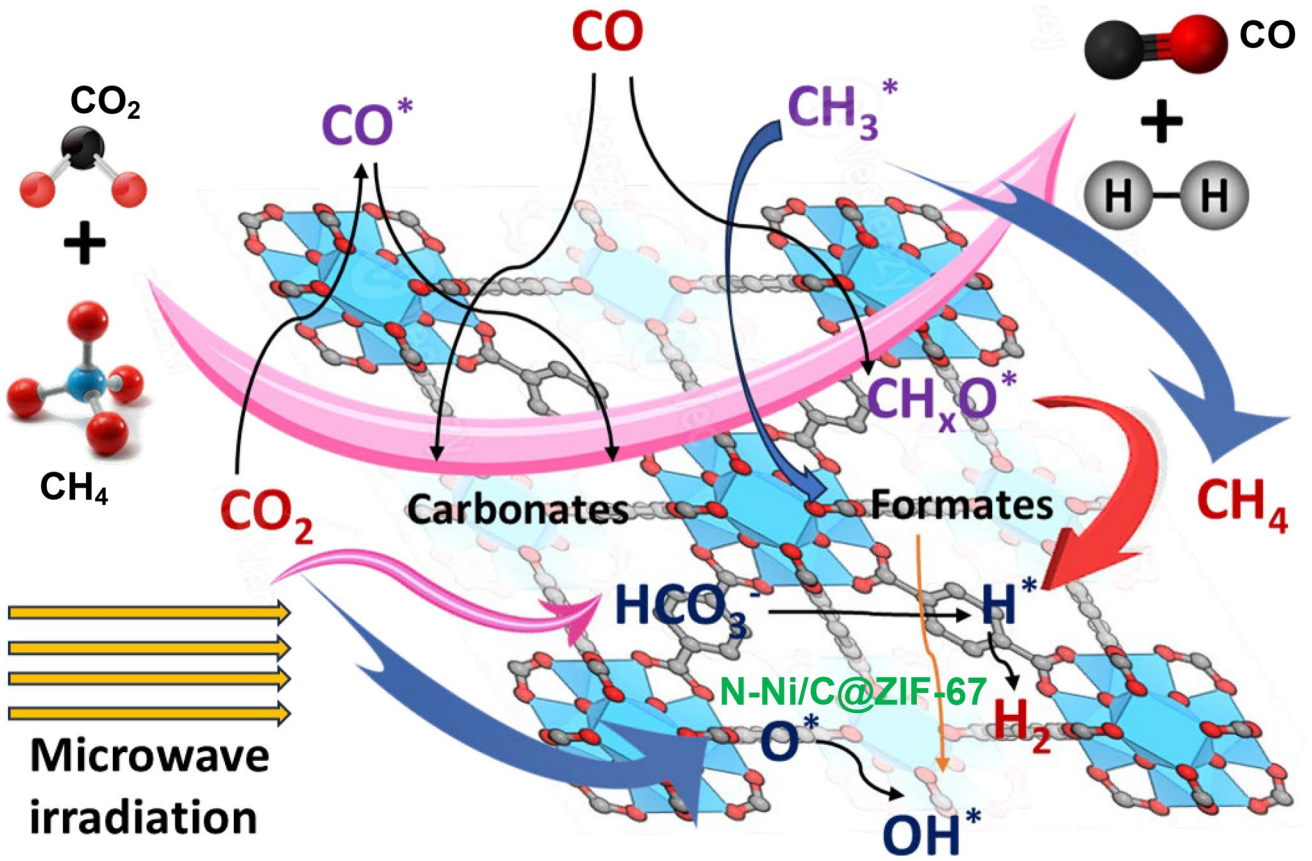

Fig. 6 Mechanism of dry reforming of methane with CO_2 over the Ni-Co/NC catalyst

It also improved the CO_2 adsorption capacity of the catalyst and prevented the carbon deposition. The N-Ni/C@ZIF-67 catalyzed DRM practice mostly transpires through the fast interactions among intermediates; formates, carbonates, and O–H groups. The Ni-Co/NC catalyst exhibited significant performance improvements, achieving methane (CH_4) conversion of approximately 93.2% and CO_2 conversion of around 94.8%.

The bi-reforming of methane (BRM) with CO_2 combines both the DRM and SRM and it has some advantage over DRM with CO_2. It expressed less C-deposition, thus, enhanced catalyst stability, and produces higher stoichiometric molecular hydrogen to carbon monoxide (H_2/CO) ratio of 2. This is more suitable and favorable for methanol synthesis and Fisher-Tropsch process (Cunha et al. 2020). Moreover, BRM produces more syngas per mole of methane compared to DRM as it combines the outputs of both DRM and SRM

$$\mathrm{BRM2CH_4 + CO_2 + 2H_2O \rightarrow 3CO + 5H_2 \Delta H_{298K}} = +220\ \mathrm{kJ/mol},\ \Delta G_{298k} = +151\ \mathrm{kJ/mol}$$

The oxy reforming of methane with CO_2 and oxygen (ORM) combines both dry reforming and partial oxidation of methane, offering unique advantages in energy efficiency and syngas composition (Choudhary and Choudhary 2008). It results in a H_2/CO ratio of 1:1, which is suitable for Fischer–Tropsch process and other processes that require low H_2/CO ratios, for example DME production.

$$\mathrm{ORM2CH_4 + CO_2 + O_2 \rightarrow 3CO + 3H_2 \Delta H_{298K}} = +58\ \mathrm{kJ/mol},\ \Delta G_{298k} = -1\ \mathrm{kJ/mol}$$

The introduction of oxygen initiates an exothermic partial oxidation reaction, which counterbalances the substantial energy requirement of the endothermic dry reforming reaction. This results in enhanced energy efficiency and diminishes external heat demands. The presence of oxygen facilitates the oxidation of surface carbon on the catalyst, hence diminishing carbon accumulation (i.e. coke formation) and preserving the catalyst activity. The thermal integration of exothermic and endothermic reactions diminishes the necessity for external heat sources, facilitating non-complicated reactor designs (Minh et al. 2021). It seems to be the most attractive (due to autothermic), but industrially not attractive due to safety limitations. Moreover, it necessitates a source of pure or virtually pure oxygen, potentially elevating operational expenses if an air separation unit (ASU) is required.

Elevated temperatures and the availability of oxygen can induce catalyst sintering and oxidation, resulting in deactivation over time. Exact optimization of CH_4, CO_2, and O_2 feed ratios is essential to prevent unwanted side reactions, including the complete methane combustion. Most of these challenges can be overcome by using solid oxides as oxygen carriers to overwhelm the direct interaction of fuel and gaseous oxygen (Li et al. 2013).

Photocatalytic reduction of CO_2

Because of the increase in population and the high standard of living, the growing demand for hydrocarbon fuel increase, so researchers were interested in finding non-conventional ways to obtain fuel from photocatalytic conversion of CO_2 as a renewable and cheap raw material source, taking into account that fixing its concentration in the atmosphere has become one of these urgent environmental requirements nowadays (Tian et al. 2022). Carbon dioxide can be obtained from multiple emission sources and can be stored in some geological formations or compressed for use in fuel production through the photocatalytic process (Saleh and Hassan 2023). For this purpose, Roy et al. (2010) used the sensitized titanium nanotube as a photocatalyst to convert carbon dioxide and water vapor into fuel comparable to fossil fuels using sunlight. In this context, CO_2 is hydrogenated on the surfaces of different catalysts at very elevated temperatures and high pressures, producing hydrocarbons, including methanol in a large proportion. Like this approach, green hydrogen is obtained from the electrolysis of water by the action of sunlight (Awad et al. 2024). The traditional thermo–chemical process to convert CO_2 to CO is an endothermic reaction ($\Delta G = +257$ kJ mol^{-1}), therefore to get 100% conversion of CO_2, the reaction temperature required is of 3075 °C at which the ΔG is of zero (Martin 1980). Traynor and Jensen Genson (2002) built a reactor to directly photolysis CO_2 at high temperatures using sunlight and achieved CO gas yield of 6%. Yet, the authors concluded that the preheating of CO_2 at about 1900 °C before exposing to sunlight radiation is more visible. Urbain et al. (2017) implemented a prototype for solar-based-photocatalytic conversion of CO_2 into syngas. That attained a solar to syngas conversion efficiency of 4.3%, and was consisted of a copper-foam-cathode coated with economical nanosized zinc flakes serving as a catalyst for the CO_2 reduction reaction (CO_2RR) to syngas, a modified silicon hetero-junction solar cell assembly functioning as a photo-anode with nickel foam as a catalyst to enhance the oxygen evolution reaction (OER), and a bipolar membrane delineating the respective catholyte and anolyte slots.

Solar energy can be used for fixation of CO_2 and water to produce chemicals such as methanol, methane and formic acid, etc. through the use of some photocatalysts such as TiO_2, SiC, ZnO, CdS, ZnS and $SrTiO_3$ semiconductors or metal complexes (Mao et al. 2013; Li et al. 2016a, b). The catalysts are suspended in water saturated with CO_2 and illuminated with solar energy via proton-assisted multiple electron-transfer processes (Rehman et al. 2022). The pioneer work was done by Inoue et al. (1979) in which different semiconductors and single crystals are used to produce CH_4, HCOOH, CH_3OH, and HCHO by illuminating aqueous solution containing CO_2. However, the low conversion is achieved when water is used as reducing agent. Yet, highly improved yields of CH_3OH and CH_4 can be achieved from the photocatalytic reaction of CO_2 with H_2O on titanium catalyst (Halmann 1983), where photocatalytic reactions proceed in the solid–gas system on the isolated tetrahedral Ti^{4+} centers dispersed on mesoporous sieves materials (Fig. 7).

As methanol is the most important product from the photocatalytic reduction of CO_2 for household and industrial purposes, many trials have been done to improve the efficiency of this process (Qu et al. 2023). Among these, Cu/SiC catalyst produces a considerable amount of methanol, ethane, and ethylene (Cook et al. 1988). Richardson et al. (2011) found an alternative way to reduce CO_2 by using organic- tertiary-amine in the electrolyte as reducing agent, by coupling photochemical reduction of CO_2 to photochemical water splitting. This strategy has proven to be effective in producing formic acid. One of the drawbacks of this interaction is finding a way to regenerate the used amine as this process is tedious. Sun et al. (2012) synthesized nanosphere of non-metallic catalyst, g-C_3N_4, with carful control of the thickness of the core–shell using porous silica as a template and demonstrated it in the photocatalytic hydrogen evolution. They concluded that the nanoarchitectures of g-C_3N_4 provided high efficiency after incorporating the Pt NPs into exterior and/or interior pores. In this context, Wang et al. (2012) developed of a facile synthesis for high efficient Pt-TiO_2 nano-films through gas-phase deposition methods. The 1D TiO_2 single crystals structure (one-dimensional) was coated with Pt NPs (0.5–2 nm) and showed an exceptional photoreduction for CO_2 to methane (1361 µmol/g-cat/h). That was attributed to the fast electron-transfer rate in TiO_2 single crystals and the efficient electron–hole separation by the Pt NPs, where the size of the Pt NPs and the unique 1D structure of TiO_2 single crystals played a significant role. Liu et al. (2013) used copper nanoparticle as co-catalyst for TiO_2 and reported an enhancement in the selectivity for methane. The authors explain their result by the presence of Cu^+ and Cu^0 and defects sites that promote the adsorption of CO_2, electron and hole trapping at different sites, in addition to the charge transfer to the adsorbed CO_2. Shown et al. (2014) used graphene oxide decorated with copper nanoparticle (4–5 nm) prepared by microwave to enhance photocatalytic reduction of CO_2 in sunlight irradiation. The Cu/GO showed significant enhancement in CO_2 reduction associated with high selectivity to methane

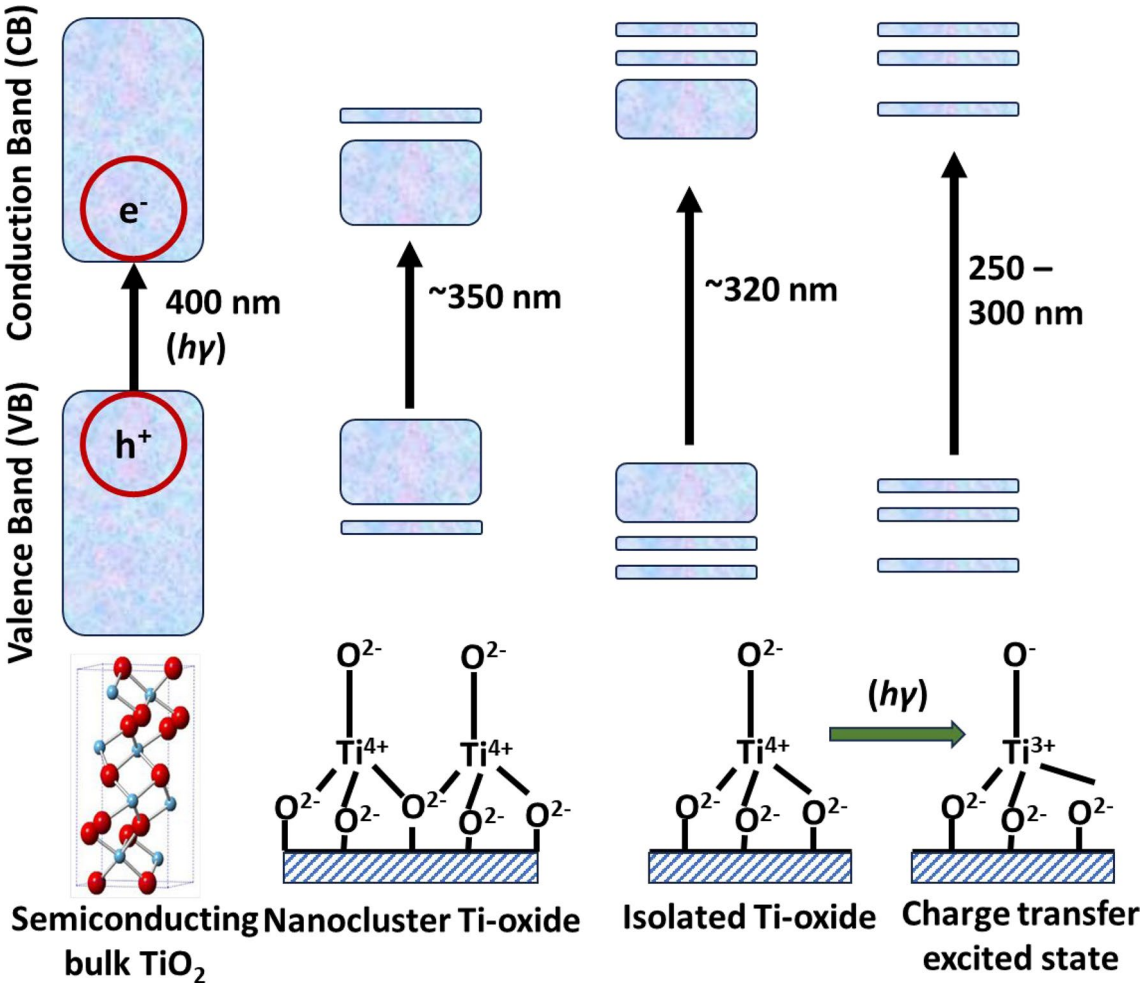

Fig. 7 The change of the electronic state in bulk TiO_2 and isolated Ti-molecular sieve

through the decreasing or suppression of electron–hole pair recombination. Kumar et al. (2014) prepared Co^{II}–phthalocyanine complexes immobilized on graphene oxide nanosheet. The catalyst showed an excellent methanol yield over all previous catalysts in the presence of sacrificial agent (triethylamine), recording by 78.7893 µmol/g-cat/h. Kuriki et al. (2016) reported binuclear ruthenium element having photosensitizer coupled with metal free semiconductor (graphitic carbon nitride; C_3N_4) as catalyst for CO_2 reduction to formic acid, in the presence of electron donor material and aqueous media, under visible light irradiation ($\lambda > 400$ nm). The catalyst activity was also compared with that of a silver decorated one ($RuRu'/Ag/C_3N_4$). The modified catalyst with Ag nanoparticles showed an excellent turnover number that was higher than 33,000, with a formic acid selectivity ranged between 87 and 99%, which was 30-times higher than that recorded for to carbon nitrile loaded with Ru(II) complex. Bera et al. (2016) reported the plasmonic effects of Au and $Au@SiO_2$, and Pt/TiO_2 loaded on $Au@SiO_2$ as support for photocatalytic conversion of CO_2. The authors prepared different sizes of $Au@SiO_2$ (2–26 nm) and studied the effect of $Au@SiO_2$ size on the catalytic performance for the reduction of CO_2. They found that the most effective size of $Au@SiO_2$ was 18 nm, while $Pt/TiO_2/Au@SiO_2$ showed considerable higher activity for methane production than Au and $Au@SiO_2$ materials due to the high dispersibility of the Pt/TiO_2 on the support and presence of SiO_2 that enhance the LSPR (localized surface plasmon resonance) of TiO_2 (Fig. 8). Sordakis et al. (2016) reported the aqueous catalytic way for CO_2 to CH_3OH at room temperature by using iridium catalyst at low pH. The iridium catalyst can hydrogenate CO_2 to formic acid at pressure of 20 bar through convenient hydrogenation pathway, and disprpportionate formic acid into methanol. By acidification with sulfuric acid the media of the reaction, the methanol selectivity reached 96%. Lee et al. (2016) reported the photocatalytic conversion of CO_2 to methane by $CuPt/TiO_2$. They found that considerable increase in the methane production is associated with decreasing the CuPt size due to the strong binding between the small CuPt NPs and CO_2, the enhancement in the protonation of CO intermediates by platinum surface atoms, in addition to the

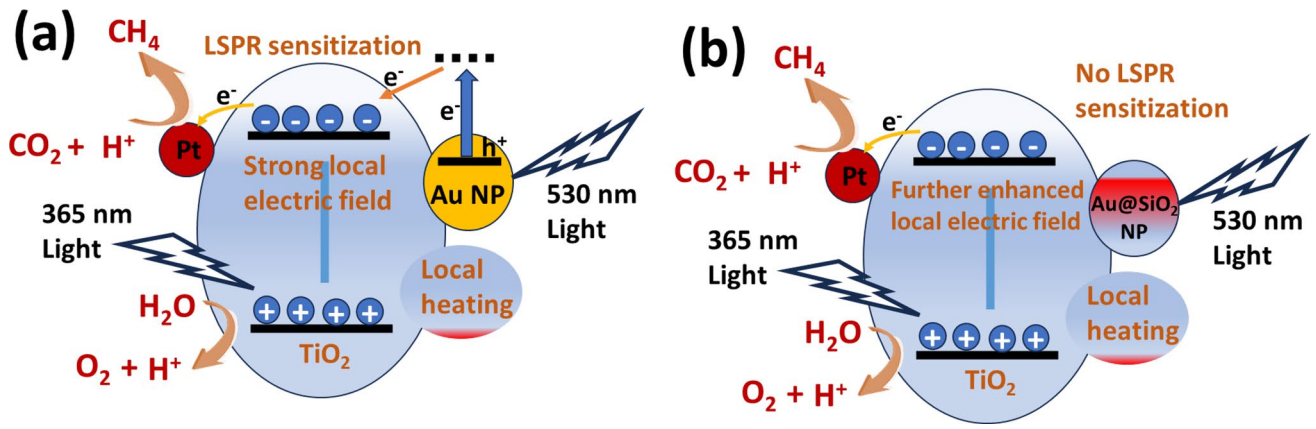

Fig. 8 The photocatalytic Pt/TiO_2/Au **a** and Pt/TiO_2/Au@SiO_2 **b** systems under co-irradiation of 365 nm and 530 nm LED lamps

reduced free energy barriers for intermediates. Furthermore, tiny nanoclusters exhibit a more robust contact with the surface of the TiO_2 support. The robust metal-support contact promotes the production of COOH, hence improving the efficiency of photocatalytic CO_2 conversion. Jiang et al. (2017) prepared a 3-dimensional quantum dots material from Bi_2WO_6 using ethylene glycol and used it as photocatalyst for CO_2-reducing to produce methanol. The prepared Bi_2WO_6 showed a considerable higher catalytic activity toward methanol. In addition, the catalyst showed long life time due to the presence of hallow 3-D structure that improves the separation of photo-generated electron–hole pairs. Miyano et al. (2017) studied different thin film of layered double hydroxides (LDHs) that have chemical formula $[M^{II}_3Ga^{III}(OH)_8]_2A{\cdot}mH_2O$ ($M^{II}=Zn^{II}$, Cu^{II}; $A^{2-}=CO_3^{2-}$, $[Cu(OH)_4]^{2-}$) for photo conversion of CO_2 at pressure of 0.40 MPa in the presence of H_2 to produce methanol. The most active photocatalyst for methanol production was $Zn_3Ga(OH)_8]_2CO_3{\cdot}mH_2O$ at a rate of 2.7 µmol/g-cat/h. Jia et al. (2017) reported an artificial photosynthetic system, which mimic the photosynthetic pathway (Fig. 9a) and yielded methanol yielded at rate of 106 µM h^{-1} cm^{-2}. It was formed from dye (Nile red) or Pd–dye embedded on photoanode (mimicking the photosystem I and Calvin cycle; plastocyanin-ferredoxin oxidoreductase) and a photocathode (mimicking photosystem II, water-plastoquinone oxidoreductase) through covalent chemical bond to produce methanol form the photoreduction of CO_2. Lin et al. (2024) developed hybrid SiC photocatalysts modified with a Fe-based co-catalyst using a simple impregnation-reduction method, resulting in an optimized local electronic structure. This catalyst achieved a remarkable photocatalytic yield of carbon-based products, reaching 30.0 µmol/g/h, and demonstrated exceptional CH_4 selectivity of up to 94.3%. That success was attributed to the electron-rich Fe co-catalyst, which enhanced the photocatalytic performance and selectivity. The synergistic effects of photo-generated electron migration and strong π-back bonding on low-valence Fe improved the adsorption and activation of reactants and intermediates in the $CO_2 \rightarrow CH_4$ conversion pathway. That work provides an innovative strategy for enhancing the multi-electron reduction capacity of semiconductor photocatalysts by using low-cost Fe as a co-catalyst instead of noble metals. Liu et al. (2024) developed BOC/In_2O_3 type II hetero-junction composite photocatalysts for photocatalytic CO_2 reduction (Fig. 9b). These composites improved the electron–hole pair separation, photo-absorption, and visible light utilization, exhibiting higher reduction efficiency than pure BOC and In_2O_3. The optimal performance was achieved with a 1% BOC/In_2O_3 mass ratio, where the BI-1 composite showed CO_2 reduction rates, which were 3.6 and 35 times higher than pure BOC and In_2O_3, respectively. That improvement was attributed to the strong interfacial contact within the heterojunction, which enhances the interfacial charge transfer efficiency.

Research gap to widespread adoption of CCS/CCUS

It has been estimated that achieving climate targets without implementing CCS will result in a potential rise of up to 140% in overall promotional mitigation costs (Ganeshan et al. 2023). Moreover, applying CCS with bioenergy plants implemented for electricity or biofuels production (i.e. BECCS) can be considered as a C-negative emission technology (Fajardy and Mac Dowell 2017). Although of the importance of CCS in mitigating the climate changes, however, the global implemented CCS plants are still low, and mainly located in USA, Canada, Norway, Brazil, United Arab Emirates, and Saudi Arabia (Kazlou et al. 2024). For example; USA has ten CCS facilities with a combined capacity to capture more than 25 million tons per annum from the production of ethanol, hydrogen, and fertilizer, in addition to power sector and natural-gas processing (Beck 2020). Studies on technology readiness levels (TRL)

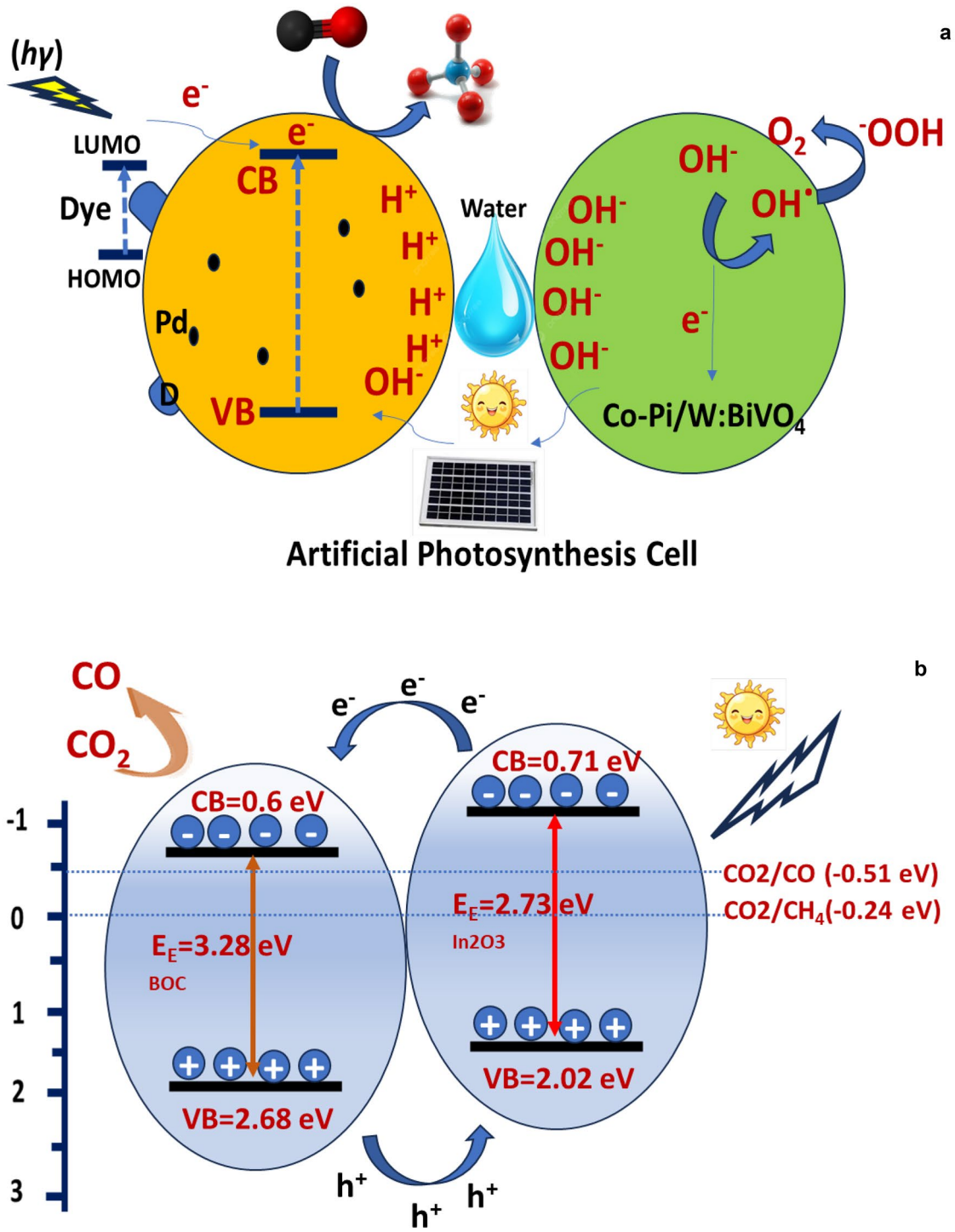

Fig. 9 **a** An artificial photosynthetic system which mimic the photosynthetic pathway; **b** a mechanism of photocatalytic reduction of CO_2

indicate that most of the CCS technologies are at level 3, signifying that more technical advancement is necessary to achieve TRL-9, which denotes the commercial scale) (Ganeshan et al. 2023). However, the post-combustion capture and EOR are considered the most prevalent CCS methods and categorized as TRL-9 (Bukar and Asif 2024). It is worth to mention that the BECCS technologies are at TRL 7–9 (Hekmatmehr et al. 2024), and a revenue of \$36–\$235/tCO_2 has been estimated from captured CO_2, upon the application of BECCS technology (Ganeshan et al. 2023). Still, as with everything new, there are a number of obstacles preventing the general implementation of CCS. CCS competes with

other climate mitigation strategies, such as renewable energy and energy efficiency measures, which are often seen as more cost-effective or less risky (Grant et al. 2021). Critics argue that CCS may prolong reliance on fossil fuels rather than promoting a transition to cleaner energy sources (Martin-Roberts et al. 2021). The financial incentives for CCS implementation, the high initial cost of CCUS technology, in addition to the effective management of storage concerns. The deployment of CCS entails substantial financial outlays for plant setup, operating costs, and different maintenance and administration costs (Bou-Hamdan et al. 2025). Hasan et al. (2015) designed a multi-scale framework for CCUS, with an estimated cost of 35.63 $/ton CO_2 captured and utilized. In another study by d'Amore and Bezzo (2017), the European supply chains for CCS and transportation are estimated to be 27–38 €/ton CO_2. However, number of variables, including process nature, separation technique, CO_2 transportation strategies, and storage site selection, have a significant impact on CCS costs (Salvi and Jindal 2019). Additionally, the cost of CCS differs according to the particular CO_2 sources, which include the electricity, cement, oil and gas, and other industries (Budinis et al. 2018). Thus, it is more preferable to apply cost assessments that should incorporate factors such as storage type, flow rate, transportation method and distance to yield more accurate cost estimate, rather than applying a permanent unit cost for CO_2 transportation via shipping or pipeline, and storing (Roussanaly et al. 2021). Identifying and assessing suitable geological formations for long-term CO_2 storage is complex and time-consuming. Besides, storage sites need to be well-characterized to ensure they can securely store CO_2 without leaks (Budinis et al. 2018). Expanding and building a strong storage infrastructure for the long-term storage of captured CO_2 could help in reducing the high upfront costs and make the CCUS more feasible. The infrastructure needed for CO_2 storage and transportation is being developed, as well as searches are being conducted to find appropriate geological formations for storing CO_2. Moreover, to guarantee safe and secure storage, this calls for the edifice of pipelines, injection wells, and extensive monitoring systems (Cao et al. 2020). The frameworks of regulations and policies serve as additional disincentives. If there are no clear-cut, all-encompassing legislation and regulations tailored to CCS and CCUS, the advancement of these technologies may impede their implementation (Bose et al. 2024). Governments must enact policies that are beneficial, such as financial incentives, supportive regulatory frameworks, and the implementation of carbon pricing mechanisms. They can promote a steady and foreseeable professional situation by doing this. International cooperation and coordination on regulatory and policy frameworks can also be helpful in addressing cross-border issues and guaranteeing a uniform strategy for the implementation of CCS globally (Frattini et al. 2024). The Department of Energy (DOE) started a storage assurance facility enterprise initiative (CarbonSAFE) on 2016, and commended the importance of setting legislations encouraging the CCS and CCUS with the increment of R&D aiming the emissions reduction in biogas and power plants, petrochemicals, fertilizers, oil and gas industries, besides, the decarbonization of shipping, aviation, plastics, cement, steel, and iron industries (Sullivan et al. 2020). Table 3 summarizes the possible effectiveness, scalability, and economic implications of CCS and CCUS approaches.

The methodology that works effectively for analyzing how developed a nation is in order to hasten the widespread implementation of CCS would briefly depend on (Rode et al. 2023);

- The values associated with carbon, such as those derived from enhanced oil recovery (EOR), carbon taxes, or emissions credits, reflect the externalities caused by pollution and serve as policy signals from governments demonstrating their commitment to a world with reduced carbon emissions (Carl and Fedor 2016). For example, USA providing a tax credit by 2008 to encourage CO_2 capture (Tarufelli et al. 2021). Currently, the credit offers up to $18/t$CO_2$ for CO_2 used EOR and $29/t$CO_2$ for CO_2 stored in geological storage. These amounts will linearly increase to $35/t$CO_2$ and $50/t$CO_2$ by 2026, respectively, and will then be adjusted for inflation (Beck 2020). This credit promotes investment in carbon capture technologies, facilitating the shift towards cleaner energy and carbon mitigation initiatives (Victor and Nichols 2022). However, inconsistencies in carbon pricing across regions hinder global adoption.
- An encouraging investment framework is required. The majority of CCS projects globally have been made possible by substantial grant assistance, with little to no debt financing (Wang et al. 2021). Banks must provide debt financing at reasonable interest rates in order to stimulate private sector investment and enable the widespread deployment of CCS. Banks currently view project risks as being excessively high, and the capital cost has a significant impact on whether or not CCS projects are approved. Debt financing will become accessible for CCS projects as the number of CCS plants rises, lowering the capital cost. To draw in private capital, governments can, nevertheless, offer additional grant financing, expedited depreciation, concessional loans, loan guarantees, and other measures in the interim. These tools provide early investors with a return on their knowledge, which may be leveraged by

Table 3 The possible effectiveness, scalability, and economic implications of CCS and CCUS approaches

CCS	CCUS
Effectiveness and limitations	
Effectiveness: CCS demonstrates a high CO_2 capture efficiency of > 90% (e.g., post-combustion amine-based processes). It is one of the most mature methods for reducing emissions from industrial and power plant sources Limitations: Long-term storage safety and leak prevention require extensive monitoring, which may affect public trust	Effectiveness: CCUS extends CCS by converting CO_2 into useful products like fuels, chemicals, and building materials. This adds economic value while reducing atmospheric CO_2 For instance, EOR enables effective storage alongside value generation Limitations: Conversion efficiencies depend on catalyst performance, which varies across applications (e.g., methanol synthesis vs. DME production)
Scalability	
CCS is highly scalable for large-scale industrial applications, particularly in power generation and heavy industries like cement and steel manufacturing Membrane systems, such as mixed matrix membranes (MMMs) or hollow-fiber systems, are modular and can be tailored for different industrial applications. Their simplicity and flexibility make them scalable for post-combustion CO_2 capture Challenges: High upfront costs for infrastructure and long-term geological storage are significant barriers. Infrastructure for CO_2 transportation (pipelines) is also critical for scalability For membrane technologies, membrane stability under impurity-laden gas streams (e.g., SO_2, NO_x) and the trade-off between selectivity and permeability limit their broader adoption	The integration of CCUS into existing industrial setups (e.g., ammonia-urea production plants) further enhances feasibility
Economic implications	
Costs: Current CCS costs range from $40–60 per ton of CO_2, with BECCS technologies yielding additional revenue ($36–$235 per ton) due to their carbon-negative nature Membrane-based systems are cost-effective for small-scale CO_2 capture due to lower energy requirements and minimal physical footprints. However, scaling up requires addressing material costs and efficiency trade-offs Economic viability: Advances in material science (e.g., graphene oxide and MXene membranes) could lower costs and improve performance, enhancing economic feasibility	Economic potential: CCUS can generate revenue streams by converting CO_2 into valuable products like blue hydrogen, methanol, and fertilizers For instance, EOR adds economic value by extracting oil while storing CO_2

project developers in the future. Even if government investments in public goods like clean air produce distributed society financial benefits rather than a private profit, they are nevertheless vital.

- The storage facilities and infrastructure accessibility are other important factors. The majority of facilities that have started up effectively so far have had access to inexpensive transportation options, like the pipeline infrastructure that is already in place to move the CO_2, as well as well-developed and characterized storage sites (Becattini et al. 2022). Therefore, it is essential that nations map and comprehend their potential to store CO_2 and assist the private sector in locating suitable locations. Governments can also finance the expansion of CO_2 pipeline networks to reduce storage expenses.

Despite these difficulties, CCUS is expected to have a bright future and its market is expanding significantly due to many causes such as the worldwide increased focus on lowering CO_2 emissions, encouraging government policies and the rising need for CO_2 for EOR (Yasemi et al. 2023) and CO_2 conversion into valued products (Bajpai et al. 2022). In addition to a variety of other clean-energy technologies, the majority of decarbonization paths that are compatible with the Paris Agreement or a net-zero-emissions scenario by the middle of the century use CCS in the power and industrial sectors (Shen et al. 2022). The Sustainable Development Scenario from the International Energy Agency (IEA), which offers a path forward for accomplishing global climate targets, adds even more impetus to this movement (Bose et al. 2024). The IEA states that a large expansion in the deployment of CCUS is necessary. Indeed, according to their estimates, CCUS

might account for as much as 7% of the total emissions reductions required by 2040 in order to achieve the critical 2-degree Celsius climate target (Dziejarski et al. 2023). It is worth to mention that, efforts performed by companies and industries to reduce their carbon footprint, can evade penalties and even acquire carbon credits, which can be exchanged for further economic advantages (Hanson et al. 2025). Ongoing R&D, governmental financial backing, and chances for scaling can reduce costs to a viable level; nevertheless, unfavorable policies and laws in certain nations have further constrained the adoption of CCUS (McLaughlin et al. 2023). Government subsidies for renewable energy, infrastructure development, and CCUS R&D can accelerate deployment. However, the withdrawal or reduction of subsidies (e.g., for renewable hydrogen production) can disrupt progress (Wu et al. 2024).

From a sustainability point of view, a very important and challenging task is to convert atmospheric CO_2 into useful and value-added organic components. This can be achieved more readily if the synthetic strategies involving newly evolved catalysts can work at atmospheric pressure and temperature of CO_2. Several reactions, for example, the CO_2 methanation process, various types of strategy, technical pathways and directions have been recently investigated. CO_2 can also be employed as a soft oxidant in the oxidative dehydrogenation of n-butane to C4 olefins, ethylbenzene to styrene or dry-reforming of ethane to syngas and ethylene. The influence of supports, promoters, size and shape of metals sites, temperature control the performance of the catalyst. The development of new lower temperature metals-based CO_2 conversion catalysts is essential to decrease the overall cost and energy consumption. Thant can be achieved via; (1) the design and investigation of different metals-based catalysts via controlling and adjusting proper composition, (2) the investigation of the relationship between the microstructure of active phase at atomic level including metals crystallographic and low temperature catalytic performance, and finally (3) investigation of the detailed kinetic and mechanistic study at low reaction temperatures.

Improper disposal and management of crop residues such as stalks and husks have both human and environmental risks, it would cause soil nutrient loss and runoff, negatively impacting the water quality (Gatkal et al. 2024), and also their decay and/or anaerobic degradation would emit toxic and corrosive H_2S, in addition to CH_4 (Czubaszek et al. 2022). Moreover, their open-burning in field leads to soil deterioration and emissions of GHG; CO, CO_2, SO_2, N_2O, CH_4, black carbon (BC), and volatile organic compounds (VOCs) (Andini et al. 2018). The effective and feasible management of such wastes is essential for mitigating environmental impacts while enhancing the agricultural sustainability. That would occur via integrating waste valorization with cutting-edge climate solutions.

Biochar can be a useful approach for a cost-effective CCUS (McLaughlin et al. 2023), whereas, lignocellulosic wastes, plant residues, micro-, and macro-algae capture atmospheric and anthropogenic CO_2, and then upon pyrolysis produces biochar, which can be applied in agriculture, industrial, wastewater treatment, and bioenergy sectors (Sakhiya et al. 2021; Dang et al. 2023; Jayakumar et al. 2023; Li et al. 2023b; Wang et al. 2023; Fan et al. 2024). Micro-algal biomass captures CO_2 producing valued products such as pigments and lipids, which would act as precursors for biofuels, bioplastics, biosurfactants, bioflocculants, and it would have different applications in food, animal feed, cosmetics, and pharmaceutical industries (Uma et al. 2022; Arora et al. 2023; Jha et al. 2024). El-Gendy and Nassar (2021, 2024) suggested a fully integrated sustainable process for wastewater treatment, valorization of CO_2, and production of different valued products and biofuels using microalgae (Fig. 10) and macroalgae (Fig. 11). Rice straw-derived biochar has been applied for CO_2 adsorption (Cabriga et al. 2023). A suggested sequential lignocellulosic wastes valorization integrated with industrial carbon dioxide capturing and valorization into valued products is summarized in Fig. 12.

Rice husks and straw are rich in silica, which can be extracted and processed into various forms suitable for catalytic applications (Nzereogu et al. 2023; Ibrahim et al. 2024). Beyond their technical advantages, these innovations align with broader sustainability goals by addressing the dual challenges of agricultural waste management and climate change mitigation. Countries with high levels of rice production, including India, China, and Southeast Asia, are uniquely positioned to leverage this approach, transforming waste into value-added materials while reducing environmental impacts (Deshpande et al. 2023). Such advancements exemplify how waste-derived resources can be harnessed to support industrial decarbonization and foster sustainable economic development. By extracting silica from these residues, it is possible to produce high-surface-area materials with exceptional thermal stability and chemical inertness, ideal for applications in CCUS technologies (Rodriguez-Otero et al. 2024). Such silica-based materials can be engineered into porous structures, serving as robust supports for catalysts and adsorbents in CO_2 capture and conversion systems (Chakroborty et al. 2023; Taiye et al. 2024). Utilizing silica derived from rice husk and rice straw as a support material in CO_2 utilization processes would offer a sustainable approach to mitigating climate change (Sakhiya et al. 2021). Functionalized silica supports, such as those impregnated with amines, exhibit superior adsorption capacities, capturing over 90% of CO_2 under optimized conditions (Leung et al. 2014; Wang et al. 2024b). Furthermore, silica-supported catalysts have proven effective in converting CO_2 into valuable products like methane,

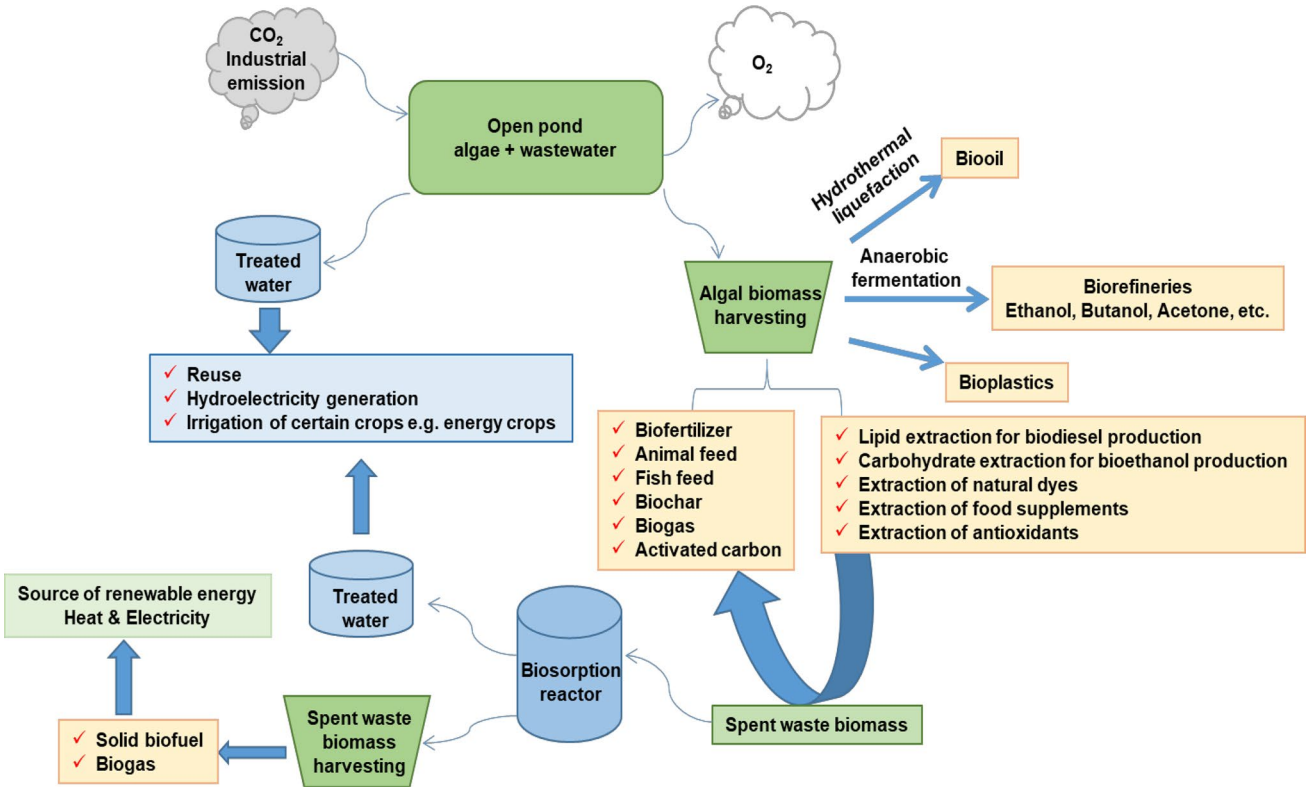

Fig. 10 A fully integrated process for wastewater treatment, CO_2 capturing, and valorization into valuable products and biofuels applying microalgae

methanol, dimethyl ether, and syngas, thereby facilitating the integration of carbon utilization into circular economy models (Barroso-Martín et al. 2020; Kiani et al. 2024; Alanazi et al. 2025). Silica's high surface area and stability enhance the dispersion and activity of metals like copper and zinc in hydrogenation processes, improving methanol yields (Kandula, et al. 2024). The high surface area and thermal stability of silica make it an excellent support for metal catalysts. Notably, silica can modify cobalt species through Co–O–SiO_n linkages, enhancing the reactivity of methoxy (*CH_3O) intermediates, which favor methanol production over hydrocarbon formation (Wang et al. 2020). Studies have demonstrated that nickel-based catalysts supported on rice husk-derived silica exhibit enhanced performance in CO_2 methanation, achieving higher methane production rates compared to those supported on commercial fumed silica. The incorporation of small amounts of ruthenium into these nickel-based catalysts further improves their reducibility and hydrogen adsorption capacity, leading to increased catalytic activity and stability (Paviotti, et al. 2021). Moreover, the high surface area and tunable porosity of silica facilitate the dispersion of active metal and acid sites, enhancing the bifunctional catalytic activity required for CO_2-to-DME conversion (Yadav 2023). Silica-based membranes also show promise in separating CO_2 from mixed gases, offering energy-efficient alternatives to conventional methods (Bui et al. 2023). Silica-based materials play a vital role as supports in these catalytic systems, enhancing the dispersion of active metals like nickel, cobalt, and ruthenium. These metals are essential for DRM due to their ability to activate CH_4 and CO_2 while minimizing coke formation (Tanimu et al. 2024). Studies have shown that silica supports with high surface area and tunable pore structures improve the thermal stability and catalytic performance of DRM systems (Karam and El Hassan 2018). Furthermore, the functionalization of silica with promoters such as cerium or zirconium oxides has been shown to enhance the oxygen storage capacity, reducing catalyst deactivation by mitigating carbon deposition during the reaction. Silica's low cost, wide availability and compatibility with various metals make it a sustainable choice for designing advanced DRM catalysts. By integrating silica-supported systems, the process achieves higher syngas yields while contributing to the dual goals of CO_2 and CH_4 mitigation (Min et al. 2024). This approach not only provides a sustainable method for utilizing agricultural waste but also contributes to the development of efficient catalysts for CCUS. Silica-supported photocatalysts have also been extensively studied for the photocatalytic reduction of CO_2, due to their high surface area and tunable porosity, which facilitate the dispersion and stabilization of active

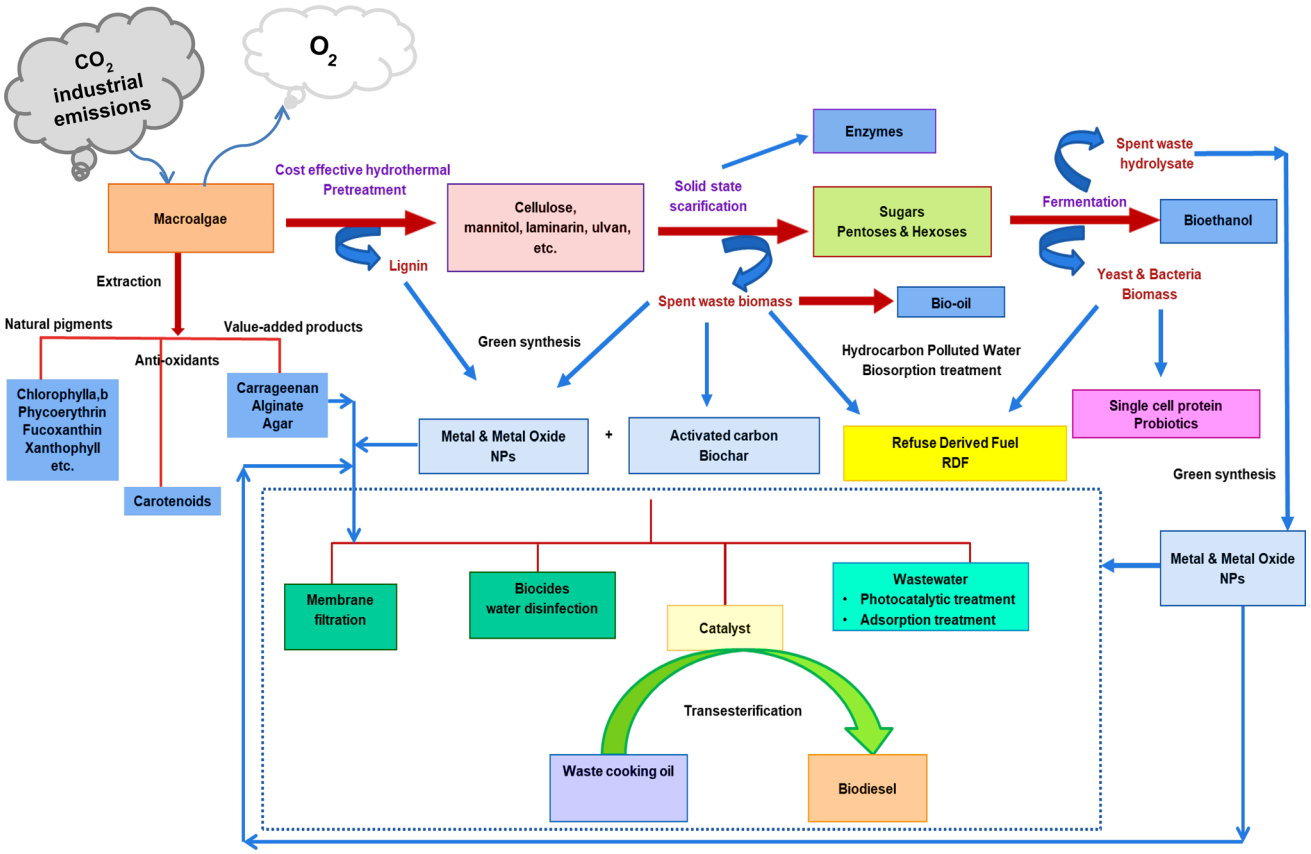

Fig. 11 A fully integrated process for CO_2 capturing, valorization into valuable products and biofuels in addition to wastewater treatment applying macroalgae

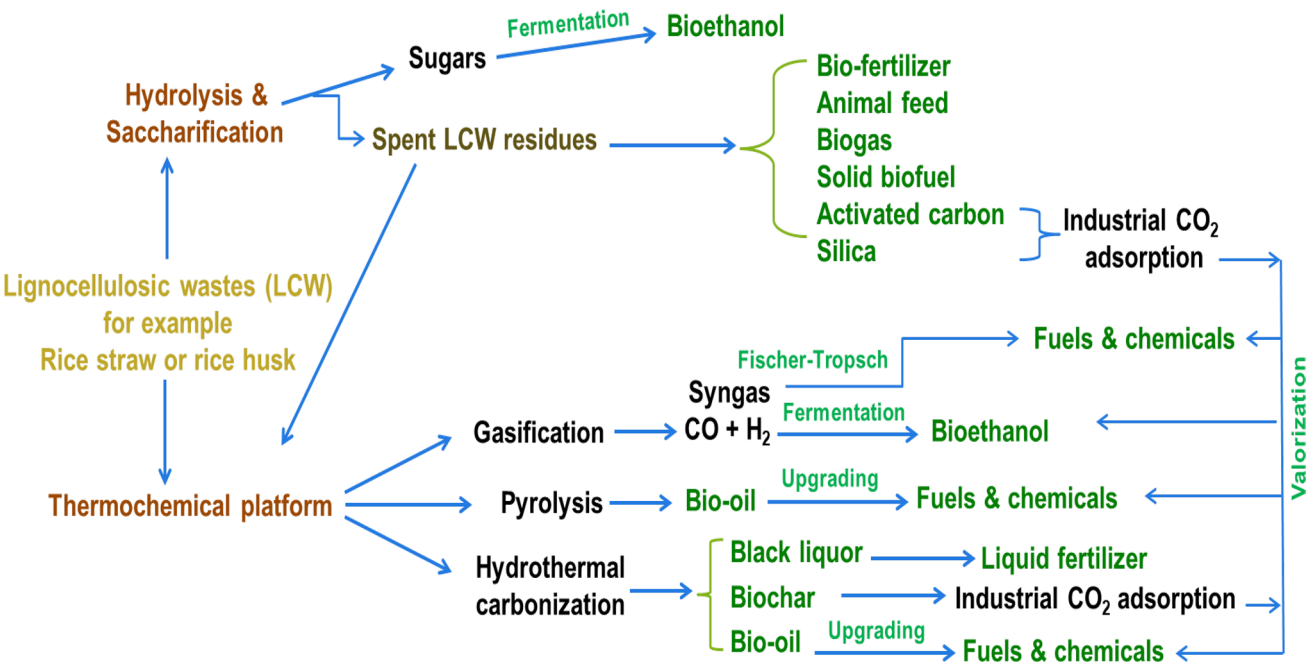

Fig. 12 A suggested sequential lignocellulosic wastes valorization integrated with industrial carbon dioxide capturing and valorization into valued products

sites (Feng et al. 2024). For instance, Ti-containing porous silica thin films with hexagonal and cubic pore structures have demonstrated the ability to convert CO_2 and water into CH_4 and CH_3OH under UV irradiation, achieving a quantum yield of 0.28% (Ikeue et al. 2002). Additionally, cobalt oxide nanoparticles immobilized on mesoporous silica particles have exhibited high efficiency in converting CO_2 to CO under visible light, with an average CO generation rate of up to 25,626 µmol/h/g and a selectivity of 83.0% (Fu et al. 2019). These studies highlight the potential of silica-supported photocatalysts in the efficient and selective reduction of CO_2, contributing to the development of sustainable energy solutions. Table 4 summarizes the possible effectiveness, scalability, and economic implications of various valorization approaches.

Uncertainties, unresolved challenges, economic feasibility, and environmental trade-offs in CO_2 valorization and CCUS technologies

Uncertainties and unresolved challenges

Despite significant advancements in carbon capture, utilization, and storage (CCUS) technologies, several critical challenges remain:

Technical challenges

Catalytic Efficiency, Stability, and Selectivity Developing catalysts that offer high activity, stability, and selectivity for CO_2 conversion reactions remains a challenge (Liu et al. 2025). Current catalysts, such as copper or nickel-based systems, often face limitations in terms of activity at low temperatures (Beniwal et al. 2025). Catalysts used in CO_2 conversion processes (e.g., $Cu/ZnO/Al_2O_3$ for methanol synthesis) often degrade over time due to sintering, poisoning by impurities (e.g., SO_2, NO_x), or changes in surface area under prolonged high-temperature operations (Berahim et al. 2023). Catalyst selectivity toward desired products, such as methanol or DME due to competing reactions like

Table 4 The possible effectiveness, scalability, and economic implications of various valorization approaches

Photocatalytic reduction	CO_2 valorization into chemicals and fuels
Effectiveness: This approach holds promise for producing high-value products like methane, methanol, and formic acid directly from CO_2, using sunlight and photocatalysts Limitations: Low efficiency and limited sunlight utilization remain critical challenges Scalability: Photocatalytic systems are still in the early research stages. Achieving industrial-scale scalability will require significant improvements in catalyst efficiency, durability, and light utilization Potential and Advances: Innovations like graphene oxide-based systems and plasmonic nanomaterials have improved product selectivity and conversion rates, but further optimization is needed for large-scale adoption Low energy input and direct utilization of sunlight make this approach attractive for distributed applications (e.g., decentralized CO_2-to-fuel production) Economic implications: Costs: Although photocatalytic reduction has low operational costs due to sunlight utilization, the development of cost-effective and durable photocatalysts is a major hurdle Economic potential: If breakthroughs in catalyst efficiency are achieved, photocatalysis could offer a low-cost alternative for decentralized CO_2 conversion, particularly in regions with abundant sunlight	Effectiveness: Converting CO_2 into methanol, DME, acetic acid, and syngas is highly effective in mitigating emissions while creating industrial feedstocks Methanol synthesis, for example, achieves CO_2 conversion rates of 30–40%, making it a promising area Challenges and limitations: Reaction conditions often require high temperatures and pressures, leading to energy-intensive processes Economic viability strongly depends on renewable hydrogen availability and the integration of renewable energy sources to reduce production costs Scalability: Industrial-scale methanol plants (e.g., $Cu/ZnO/Al_2O_3$-based catalysts) and DME production facilities are already operational, demonstrating high scalability Economic Implications: Costs: Methanol production costs are expected to decline by 2050 due to reduced renewable energy prices, making renewable methanol competitive with fossil-derived alternatives Market impact: Methanol, DME, and acetic acid are high-demand chemicals, ensuring economic feasibility. However, processes like methanol synthesis require substantial upfront investments in renewable hydrogen infrastructure

the reverse water–gas shift (RWGS) reaction (Huang et al. 2024).

Membrane Stability Membrane-based CO_2 capture technologies face issues related to stability, fouling, and the trade-off between permeability and selectivity (Osman et al. 2024). For instance, polymeric membranes often degrade when exposed to acidic gases like SO_2 and NO_x, which are typically present in flue gases (Mollahosseini et al. 2025).

Energy Intensity CO_2 conversion processes, including photocatalysis or electrochemical reduction, often have high energy demands. For example, the DRM and photocatalytic reduction require elevated temperatures or high-intensity light sources, leading to significant energy consumption (Yergaziyeva et al. 2024).

CO_2 Capture Efficiency Technologies like post-combustion chemical absorption (e.g., amine-based solvents) have demonstrated high capture efficiencies (> 90%), but their scalability is constrained by high energy requirements for solvent regeneration. That adds to the uncertainty to their economic and environmental performance (Hanson et al. 2025). Photocatalytic and electrochemical reductions of CO_2, while promising, exhibit low quantum efficiencies and high energy consumption, which would limit their practical application (Yergaziyeva et al. 2024).

Feedstock Quality The presence of impurities in CO_2 streams (e.g., from flue gases) affects catalyst activity and separation efficiency in membrane technologies and chemical looping processes (Zhang et al. 2024b). Processes relying on pure or near-pure CO_2 streams face additional costs for pre-treatment and purification (Thiedemann and Wark 2025).

Integration with Existing Infrastructure Transitioning from fossil fuel-based energy systems to CCUS-integrated systems requires retrofitting existing industrial plants, which presents logistical and technical hurdles (Acampora et al. 2025).

Economic challenges

High Costs of Implementation The initial capital and operating costs associated with CCUS are prohibitive for many industries. For example, the estimated cost of capturing CO_2 ranges from $40–60 per ton, depending on the capture method and source (Soo et al. 2024). These costs must be reduced to achieve widespread adoption.

Cost Variability The cost of CO_2 capture and utilization varies significantly depending on the technology used, the scale of operation, and geographical location (Hanson et al. 2025). For instance: Chemical absorption processes incur high energy penalties for solvent regeneration (~ 30% energy loss in power plants) (Demir et al. 2022). Membrane-based separation technologies, while modular, require further reduction in material costs (Dai and Deng 2022). Market fluctuations in the prices of catalysts, renewable energy, and raw materials (e.g., hydrogen for hydrogenation processes) introduce further economic uncertainty (Ramirez-Corredores 2024; Segovia-Hernández et al. 2025). Finally, the economic feasibility of CCUS technologies is highly sensitive to carbon pricing mechanisms and government subsidies. Inconsistent policies across regions hinder global adoption and investment (Ampomah et al. 2024).

Market Uncertainty Economic incentives for CO_2 utilization are weak due to limited market demand for CO_2-derived products (e.g., methanol, DME). That creates uncertainty around the economic viability of large-scale deployment (Hanson et al. 2025). For instance, only around 110 million tons of CO_2 are currently utilized annually, primarily in EOR and urea production, compared to billions of tons emitted globally (Dong 2025).

Technology Readiness Levels (TRLs) Many promising technologies, such as chemical looping and photocatalytic reduction of CO_2, are still at low TRLs (TRL 3–4) and require further development to reach commercial viability (LeClerc et al. 2025).

Policy, social acceptance, and regulatory barriers

Lack of Universal Standards Inconsistent policy frameworks across regions, create uncertainty for stakeholders and investors, and consequently, hinder international cooperation and investments in CCUS technologies (Bou-Hamdan et al. 2025). For example, while some nations provide tax credits for carbon capture (e.g., the U.S. offers $50/t$CO_2$ for geological storage), other regions lack similar incentives.

Risk of Prolonged Fossil Fuel Use Critics argue that CCUS technologies may prolong the reliance on fossil fuels, as they offer a pathway to continue their use instead of transitioning to renewable energy systems (Hanson et al. 2025). Moreover, permitting processes for geological storage and infrastructure development can be time-consuming and inconsistent across jurisdictions (El Farsaoui et al. 2025).

Public Perception Social acceptance of CCUS technologies, particularly geological storage, is influenced by concerns about safety, CO_2 leakage risks, and land-use conflicts. Addressing these concerns through transparent communication and engagement is critical (Tardin-Coelho et al. 2025).

Economic feasibility

Cost reduction strategies

Optimization of Capture Systems Using advanced materials like MOFs or ILs for CO_2 capture has the potential to reduce costs by increasing efficiency and minimizing energy requirements for regeneration (Ma et al. 2025).

Scaling Renewable Methanol Production Green methanol, produced from captured CO_2 and renewable hydrogen, could become economically competitive as the cost of renewable energy drops. Projections suggest costs could fall to $250–630/ton by 2050 (Müller et al. 2025).

Revenue Streams from CO_2 Utilization Valorization of CO_2 into high-value chemicals like methanol, DME, and acetic acid can offset carbon capture costs. However, market expansion for these products is necessary to accommodate large-scale CO_2 utilization (Podder et al. 2023).

Government Incentives and Carbon Pricing Policies such as carbon taxes, emissions trading systems, and subsidies for CCUS projects can improve economic feasibility (Hanson et al. 2025). For instance, the European Union's Emissions Trading System (ETS) provides financial incentives for reducing CO_2 emissions (Zhao et al. 2024).

Cost comparisons

CCS vs. CCUS Geological storage of CO_2 is generally less expensive than its conversion into chemicals or fuels. However, storage presents long-term monitoring costs and risks of leakage (Bashir 2024).

Technologies like post-combustion capture and green hydrogen production remain expensive, with costs ranging from $40–60 per ton of CO_2 (Soo et al. 2024). Yet, carbon pricing mechanisms and subsidies (e.g., tax credits in the USA) are critical to bridge financial gaps (Mengesha and Roy 2025).

Industry-Specific Costs The costs of CCUS implementation vary by industry. For example, capturing CO_2 from cement or chemical plants is more expensive than from power plants due to differences in flue gas composition and flow rates (Hanifa et al. 2023).

Economic co-benefits

Job Creation The deployment of CCUS technologies can create jobs in manufacturing, infrastructure development, and research. Industries related to renewable energy integration and CO_2-derived products also stand to benefit (Zentou et al. 2025).

Energy System Resilience CCUS can act as a "bridge technology" to facilitate a smoother transition to renewable energy systems by decarbonizing existing fossil fuel infrastructure (Abdallah et al. 2024).

Environmental trade-offs

Energy consumption and emissions

Energy Penalty High energy requirements in processes like DAC (Li et al. 2024), photocatalysis, electrochemical reduction (Yergaziyeva et al. 2024), and amine-based CO_2 capture (Demir et al. 2022) may result in higher indirect emissions, specially, if the energy is derived from fossil fuels. That may raise concerns about the net carbon footprint and scalability.

Lifecycle Emissions The full lifecycle of CCUS technologies, including material extraction, equipment manufacturing, and transportation, must be considered (Hanson et al. 2025). For example, producing and transporting materials, for example; catalysts, amine solvents, or membranes can generate emissions, partially offsetting the benefits of CO_2 capture (Nwabueze and Leggett 2024). Moreover, long-term risks, such as CO_2 leakage from geological storage reservoirs, require extensive monitoring and add to operational uncertainty (Xiao et al. 2024).

Resource intensity

Water Usage The water footprint of CCS varies from 0.74 to 575 m^3 H_2O per tonne of CO_2, contingent upon the technique employed (Rosa et al. 2021). Bioenergy with CCS reported to possess the most substantial water footprint per tonne of CO_2 recovered, which mostly attributable to the significant water demands linked to transpiration (Rosa et al. 2021). The extensive implementation of CCS to achieve the Paris Agreement target of limiting global warming to 1.5 °C would nearly double the anthropogenic water footprint, which may exacerbate water scarcity in arid regions (Xie et al. 2021).

Raw Material Demand Advanced capture materials, such as MOFs or rare earth elements used in catalysts, require mining and processing, which can lead to land degradation, biodiversity loss, and additional emissions (Soo et al. 2024).

Risk of leakage

Geological Storage While geological storage is considered safe, the risk of CO_2 leakage from storage sites remains a concern. Monitoring and mitigation strategies are required, adding to the overall cost and complexity (Bashir et al. 2024).

Ocean Acidification Some proposed CO_2 storage methods, such as ocean sequestration, could exacerbate ocean acidification, negatively impacting marine ecosystems (Zhang et al. 2025).

Social and ecological impacts

Land Use Conflicts Deploying large-scale CCUS infrastructure, such as pipelines and storage facilities, may require significant land use, leading to potential conflicts with local communities and ecosystem (Tardin-Coelho et al. 2025).

Biodiversity Loss The construction of CCUS facilities and the extraction of raw materials for advanced technologies could disrupt habitats and threaten biodiversity (Hanson et al. 2025).

Future directions and recommendations

Interdisciplinary collaboration

Collaboration between academia, industry, and governments is essential to accelerate research and development of CCUS technologies, address technical bottlenecks, and scale up promising solutions.

Policy and financial support

Governments must implement supportive policies, such as carbon pricing, tax credits, and subsidies, and establish clear regulations for CO_2 storage and utilization to encourage private sector investment.

Focus on renewable integration

Emphasizing the integration of CCUS with renewable energy systems can reduce the energy penalty and improve the overall sustainability of these technologies. For example, coupling CCUS with green hydrogen production can create synergies that enhance economic and environmental outcomes.

Sustainability metrics

Comprehensive lifecycle assessments (LCA) should be conducted for all CCUS technologies to evaluate their environmental and economic trade-offs, including raw material sourcing, energy consumption, and end-product value.

By addressing these challenges and trade-offs, the implementation of CCUS technologies can be optimized to achieve climate change mitigation goals while fostering a sustainable, low-carbon future.

Valorization of CO_2 into valued products and sustainability

The article discusses multiple technologies for CO_2 capture, conversion, and utilization, with a focus on their potential to tackle climate change and align with global climate policies, such as the Paris Agreement and Sustainable Development Goals (SDGs). Tables 5 and 6 structured comparative analysis of the reviewed technologies and their alignment with these policies. CCS/CCUS align with Paris agreement with its goal to limit global temperature rise to 1.5 °C. CCUS

Table 5 Comparative analysis of CO_2 capture technologies and their alignment with global climate policies

CO_2 capture technologies			
Post-combustion capture	Membrane separation	Chemical looping	Cryogenic separation
Description: Involves capturing CO_2 from flue gas using chemical solvents (e.g., amines) Advantages: High capture efficiency (> 90%); established commercial viability Challenges: High energy consumption due to solvent regeneration; adds an energy penalty of ~ 30% to power plant output Alignment with climate policies: Supports Paris Agreement goals by reducing emissions from fossil fuel power plants Aligns with SDG7 (Affordable and Clean Energy) by enabling transitional decarbonization	Description: Selectively separates CO_2 from gas mixtures using polymeric or inorganic membranes Advantages: Low energy consumption; high modularity; minimal physical footprint Challenges: Trade-offs between selectivity and permeability; vulnerability to impurities (e.g., SO_2, NO_x) Alignment with climate policies: Advances SDG9 (Industry, Innovation, and Infrastructure) by promoting energy-efficient technologies Contributes to SDG13 (Climate Action) by enhancing CO_2 capture efficiency	Description: Transfers oxygen using metal oxides to produce a nearly pure CO_2 stream Advantages: High efficiency; reduced energy demand compared to amine-based systems Challenges: Early development stage; scalability issues Alignment with Climate Policies: Contributes to long-term decarbonization pathways (aligned with Paris Agreement) Supports SDG12 (Responsible Consumption and Production) by reducing process waste	Description: Liquefies CO_2 at low temperatures for separation Advantages: Suitable for CO_2-rich streams Challenges: High energy costs; potential clogging Alignment with Climate Policies: Limited applicability due to high energy demand, potentially conflicting with SDG7

Table 6 Comparative analysis of CO_2 valorization technologies and their alignment with global climate policies

CO_2 valorization technologies				
Methanation	Hydrogenation to methanol	DME production	Syngas production	Photocatalytic reduction
Description: Converts CO_2 into methane using hydrogen via the Sabatier reaction Advantages: Enables renewable energy storage; integrates with biogas upgrading Challenges: Catalyst deactivation at high temperatures; limited scalability Alignment with Climate Policies: Supports SDG9 by enabling innovative energy storage solutions Contributes to SDG13 by reducing GHG emissions	Description: Converts CO_2 into methanol using renewable hydrogen Advantages: Methanol can serve as a fuel, chemical feedstock, and energy carrier Challenges: High energy demand for green hydrogen production; catalyst optimization required Alignment with climate policies: Enhances SDG7 by integrating renewable energy with chemical production Advances SDG12 and SDG13 by fostering circular carbon utilization	Description: Produces DME via CO_2 hydrogenation and methanol dehydration Advantages: Clean-burning fuel; compatibility with existing fuel infrastructure Challenges: High energy demand; requires bifunctional catalysts Alignment with climate policies: Aligns with SDG7 by promoting alternative, clean fuels Contributes to SDG11 (Sustainable Cities and Communities) by reducing urban air pollution	Description: Converts CO_2 and CH_4 into syngas via dry reforming or bi-reforming Advantages: Utilizes two major GHGs (CO_2 and CH_4); produces versatile feedstock for fuels and chemicals Challenges: High operating temperatures; coke formation on catalysts Alignment with climate policies: Reduces GHG effects, supporting SDG13 Facilitates industrial decarbonization, advancing SDG9	Description: Reduces CO_2 to value-added chemicals or fuels using solar energy Advantages: Utilizes renewable energy; potential for low-temperature operation Challenges: Low efficiency; early TRL Alignment with Climate Policies: Strongly supports SDG7 and SDG13 by integrating solar energy with carbon utilization
Suggested technology adoption roadmap for integrating CO_2 valorization technologies into industrial processes				
*Short-Term strategy (0–5 years)	*Short-Term strategy (0–5 years)	**Medium-Term strategy (5–15 years)	**Medium-Term strategy (5–15 years)	***Long-Term strategy (> 15 years)

*Short-Term; high-impact and TRL technologies with low carbon intensity and emphasize pathways that offer immediate economic returns and align with existing infrastructure

**Medium-Term; scale up medium-TRL technologies and requires investment in infrastructure to support modular and scalable solutions, such as advanced membranes

***Long-Term**;** emerging technologies with high carbon intensity reductions but with low TRL, and requires R&D for the development of novel catalysts and materials to reduce costs and enhance efficiency

technologies directly reduce emissions from major industrial sources, while, conversion technologies foster a circular carbon economy, reducing net emissions. Limited pipeline networks and storage sites still pose logistical challenges. However, the investments in infrastructure directly address SDG9 and Paris Agreement targets. Carbon dioxide valorization into useful and valued products directly corresponds with the United Nations SDGs and their three interrelated pillars: society, economy, and environment. This innovative method offers transformative key for addressing climate change and promoting the broader goals of sustainable development, ensuring a balanced and equitable future for people and the planet. Valorizing CO_2 into chemicals such as acetic acids, dimethyl ether, formic acids, etc., which can act as feedstock for different industries (Cui et al. 2022), fuels such as methanol, methane, syngas, etc. (Awogbemi and Desai 2025), and other materials such as polymers (Ramirez-Corredores 2024) and constructing materials (Li et al. 2022) can reduce GHG emissions, helping to combat climate change by utilizing CO_2 as a resource rather than a pollutant. That would achieve the SDG13 of climate action, since valorization of CO_2 would decrease production costs while concurrently diminishes the carbon footprint of industrial activities (Bose et al. 2024). The decrease in GHG emissions would prevent the direct and indirect air, soil, and water pollution, decrease oceans and sea acidification, and mitigate the eutrophication phenomenon (Hanson et al. 2025), thus saves life on land and underneath water, achieving SDG14 and SDG15 (Chlela and Selosse 2023), besides protecting the availability of drinking water SDG6 (Ghiat and Al-Ansari 2021). It would also achieve SDG11 of sustainable cities and communities via sustainable architecture and by reducing emissions from urban centers and industrial zones. Valorization of CO_2 contributes to cleaner cities, improving air quality and fostering

sustainable urban development (Alli et al. 2024). Moreover, it would achieve the SDG12 of responsible production and consumption, via the integration of CO_2 valorization into industrial processes and recycling waste CO_2 into useful products and fuels. This would also reduce the dependency on exported energy, fuels and save the non-renewable fuel reserves. Thus, fostering a circular carbon economy and diminishing reliance on non-renewable resources (Alli et al. 2024). It would also contribute to the development of low-carbon energy systems, supporting the global energy transition and achieving the SDG7 of affordable and clean energy (Saleh and Hassan 2023). When utilizing CO_2 for producing fertilizers (Cheng et al. 2024), it would help in supplying the food-chain and overcome hunger, achieving SDG2 (McLaughlin et al. 2023). The advancement and expansion of CO_2 valorization technologies generate new sectors and employment prospects, especially in research, manufacturing, and infrastructure development, thus, achieving SDG8 of decent work and economic growth, in addition to no poverty SDG1 (Otto et al. 2015; Mikunda et al. 2021). Not only these, but it would also achieve SDG10 of reduced inequalities, as implementing CO_2 valorization technology in developing nations can facilitate equal access to renewable energy supplies and sustainable national manufactured CO_2-goods, hence diminishing inequities among countries (Chlela and Selosse 2023). Valorization propels industrial innovation, promoting the integration of innovative technologies that combine CO_2 capture and utilization in different industrial sectors, achieving SDG9 of industry, innovation, and infrastructure (Mikunda et al. 2021). Mitigating CO_2 emissions by valorization enhances air quality, hence alleviating health hazards linked to pollution and climate-related diseases, consequently achieving SDG3 of good health and well-being (Chlela and Selosse 2023). Briefly, technologies like methanation, hydrogenation, and photocatalysis integrate renewable energy into industrial processes, thus align with SDG7. Advances in membranes and catalytic systems enhance industrial innovation, thus align with SDG9. Circular carbon utilization reduces reliance on non-renewable resources, thus align with SDG12. All reviewed technologies contribute to climate action by mitigating GHG emissions, thus align with SDG13. Uneven adoptions of carbon pricing and regulatory frameworks hinder international progress. Yet, incentivizing industry adoption through subsidies and tax credits supports SDG12 and SDG13. Finally, advancing CO_2 valorization requires multidisciplinary and interdisciplinary collaboration across academia, industry, and governments, fostering partnerships to accelerate innovation and implementation, thus achieving the SDG17 of partnerships for the goals (Mikunda et al. 2021). Not only has that, but establishing clear, global standards for CCUS also aligns with SDG17.

Conclusion

Anthropogenic CO_2 emissions are a primary driver of global climate change, necessitating urgent and innovative strategies to reduce atmospheric CO_2 levels while fostering a sustainable environment. The reduction of GHG emissions, especially CO_2, and their continuous use, via the creation of an effective utilization from it, is vital to the continued life on earth, is considered difficult to challenge. However achieving this challenge offers a real opportunity for sustainable energy and environmental development. Research on CO_2 conversion is essential and must be an integral part of research and development for carbon management and sustainable development. This article review provides a preliminary overview for defining the scope, potential, and limitations of CO_2-conversion into valuable chemicals with different industrial applications, highlighting their role in promoting a circular carbon economy. Despite significant progress, challenges persist in scaling up these technologies due to economic, technical, and policy-related barriers.

Key takeaways

Effectiveness CCS and CCUS currently lead in effectiveness due to their high capture efficiency and ability to integrate with existing industrial processes. Chemical valorization offers significant potential for creating valuable products but requires high energy inputs. Thus, the integration with renewable energy sources would minimize the carbon footprint of CO_2 conversion technologies, reduce energy penalties, and enhance sustainability.

Scalability CCS and chemical conversion technologies (e.g., methanol and DME production) are more scalable at the industrial level. Membrane technologies are promising for modular applications, while photocatalysis requires further development for large-scale adoption. Thus, the increase of government and private-sector funding would address the technical and economic barriers, particularly for early-stage technologies like photocatalysis.

Economic Implications CCUS offers the best economic returns through value-added products like blue hydrogen and methanol. Photocatalysis, while cost-effective in operation, needs breakthroughs in catalyst development to become economically viable. Thus, focusing on development

of low-cost, efficient catalysts for CO_2 conversion (e.g., metal–organic frameworks, graphene-based systems), is essential.

Policy Harmonization Increase the awareness of stakeholders and the public about the environmental and economic benefits of CCUS, and the alignment of international policies to incentivize CCUS adoption, including carbon pricing, tax credits, subsidies, clear and consistent regulatory frameworks, and cross-border CO_2 transportation agreements are also critical factors for gaining social acceptance and enhance investment.

Synergistic Approaches and LCA Performance of comprehensive LCA to analyze the environmental trade-offs of CCUS, encompassing raw material extraction, energy use, and end-product disposal, would guarantee the net environmental advantages correspond with sustainability objectives. Investigate the synergies between CCUS and other climate solutions, including bioenergy, waste valorization, and industrial decarbonization, in addition to the integration of CO_2 capturing with biochar production or algal biomass utilization might improve resource efficiency and generate supplementary revenue streams.

The reviewed technologies demonstrate significant potential in mitigating climate change and aligning with global climate policies. While economic and technical challenges persist, advancements in CO_2 capture and conversion can drive a sustainable, low-carbon future. Thus, more research is necessary towards effective CO_2 conversion into more useful substances using renewable sources of energy and cost-effective catalysts derived from abundant lignocellulosic biomass. The interdisciplinary collaboration, supportive policies and regulatory frameworks, and substantial investment in R&D are essentially required to accelerate the adoption of CCUS technologies, overcome existing barriers and unlock their full potential to achieve the climate change mitigation goal and the sustainability goals with its three pillars economy, society, and environment. Yet, by advancing CO_2 valorization, we can pave the way toward effective climate change mitigation and a sustainable, low-carbon future. Moreover, by fostering international collaboration and supporting innovation, CCS/CCUS technologies can play a pivotal role in achieving the Paris Agreement goals and SDGs.

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Data availability Data are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval We declare that all authors of this manuscript have made substantial contributions. We have not excluded any author that substantially contributed to this manuscript. We have followed our ethical norms established by our respective institutions.

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