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# Nanomaterials and hybrid nanocomposites for CO<sub>2</sub> capture and utilization: environmental and energy sustainability

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Anthropogenic carbon dioxide (CO<sub>2</sub>) emissions have dramatically increased since the industrial revolution, building up in the atmosphere and causing global warming. Sustainable CO<sub>2</sub> capture, utilization, and storage (CCUS) techniques are required, and materials and technologies for CO<sub>2</sub> capture, conversion, and utilization are of interest. Different CCUS methods such as adsorption, absorption, biochemical, and membrane methods are being developed. Besides, there has been a good advancement in CO<sub>2</sub> conversion into viable products, such as photoreduction of CO<sub>2</sub> using sunlight into hydrocarbon fuels, including methane and methanol, which is a promising method to use CO<sub>2</sub> as fuel feedstock using the advantages of solar energy. There are several methods and various materials used for CO<sub>2</sub> conversion. Also, efficient nanostructured catalysts are used for CO<sub>2</sub> photoreduction. This review discusses the sources of CO<sub>2</sub> emission, the strategies for minimizing CO<sub>2</sub> emissions, and CO<sub>2</sub> sequestration. In addition, the review highlights the technologies for CO<sub>2</sub> capture, separation, and storage. Two categories, non-conversion utilization (direct use) of CO<sub>2</sub> and conversion of CO<sub>2</sub> to chemicals and energy products, are used to classify different forms of CO<sub>2</sub> utilization. Direct utilization of CO<sub>2</sub> includes enhanced oil and gas recovery, welding, foaming, and propellants, and the use of supercritical CO<sub>2</sub> as a solvent. The conversion of CO<sub>2</sub> into chemicals and energy products *via* chemical processes and photosynthesis is a promising way to reduce CO<sub>2</sub> emissions and generate more economically valuable chemicals. Different catalytic systems, such as inorganics, organics, biological, and hybrid systems, are provided. Lastly, a summary and perspectives on this emerging research field are presented.

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## 1. Introduction

The research related to organic–inorganic hybrid nanocomposites is gaining momentum, and large amounts of data are being generated from different research groups and real fields to tailor the properties of nanomaterials towards their optimal performance. Energy production *via* fossil fuel combustion plays a critical role in carbon dioxide (CO<sub>2</sub>) emissions. In an unprecedented way, there is a fast growth of CO<sub>2</sub> levels that disturb the earth's climatic conditions.<sup>1</sup> Therefore, controlling and balancing CO<sub>2</sub> emissions while meeting global energy demand is critical. CO<sub>2</sub> capture, utilization, and storage (CCUS) technologies are the best options for reducing global warming while addressing the energy crisis.<sup>2</sup> Therefore, it is essential to create renewable energy sources to reduce the effects of global warming and satisfy the rising demand for energy.<sup>3–5</sup> The CO<sub>2</sub> released by industries and the burning of

fossil fuels is collected and stored using carbon management technologies such as CCUS. The captured CO<sub>2</sub> can also be transformed into various high-value chemicals and fuels, addressing pollution control and energy supply issues. This review introduces the CO<sub>2</sub> cycle with emission sources, storage, and utilization. Different forms of CO<sub>2</sub> utilization are divided into two categories: non-conversion utilization (direct use) and conversion of CO<sub>2</sub> to chemicals and energy products.

## 2. CO<sub>2</sub> sources and emission

Several sources of CO<sub>2</sub> emission cause an increase in its concentrations in the atmosphere. The CO<sub>2</sub> sources can be classified into natural and human sources. Natural sources include decomposition, plant and animal respiration, ocean release and respiration, and volcanic eruptions. Human sources, which are sources of anthropogenic emissions, include activities such as cement production, deforestation, and the burning of fossil fuels like coal, oil, and natural gas. Some other sources include electricity, heat sector, transportation, and industries. Human activities such as burning oil, coal, and gas, as well as deforestation, are the primary sources of CO<sub>2</sub> emission. The atmospheric concentration of CO<sub>2</sub> has been rising

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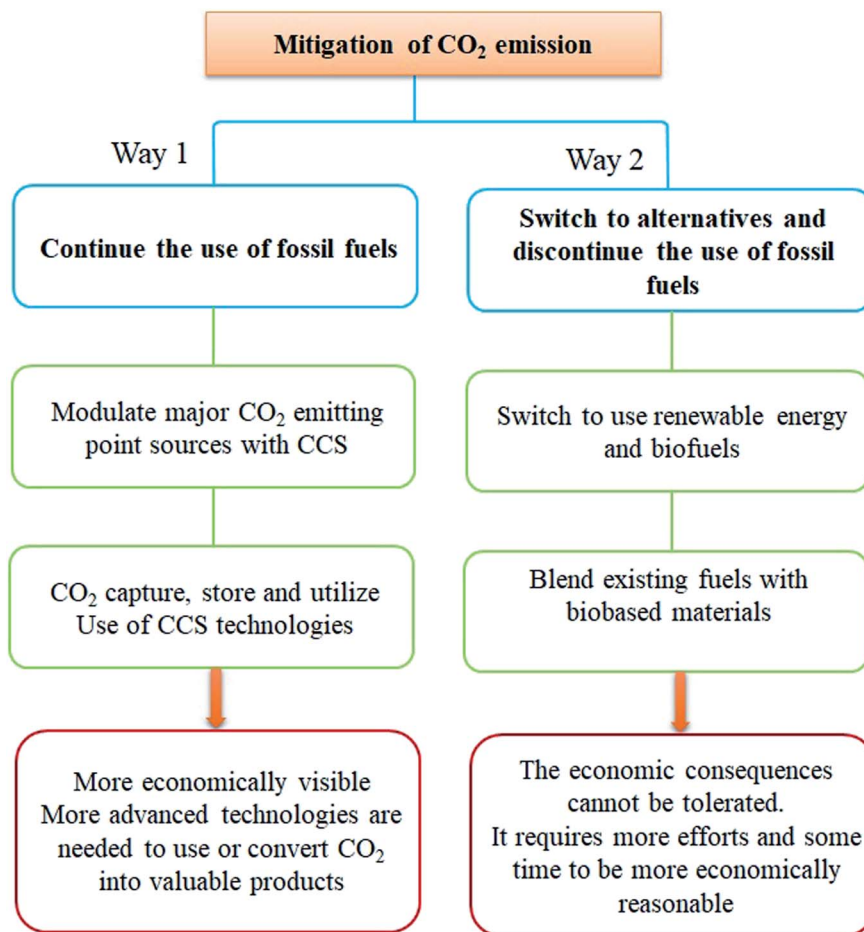


Fig. 1 Possible mitigation of CO<sub>2</sub> emissions.

extensively due to human activities, including the industrial revolution. Human sources of emissions have upset the natural balance by adding extra carbon dioxide to the atmosphere without removing any.

The increase in the global atmospheric concentration of anthropogenic greenhouse gases (GHG), including CO<sub>2</sub>, leads to global warming and climate change. The increase in such gases causes ozone layer depletion, which in turn causes the greenhouse effect and global warming, and ultimately climate change. Climate change decreases worldwide agricultural productivity because of low rainfall, changing seasons, and rising temperatures. Global warming, ocean acidification, desertification, and changing weather conditions could all be made worse by the high level of industrial pollution and the indiscriminate production of greenhouse gases into the atmosphere. But among the immediate effects of climate change are issues with food security, migration, health issues, rising sea levels, and severe storms that affect coastal regions.<sup>4</sup> The increase in CO<sub>2</sub> may also indicate a negative impact on the environment, which indicate a decrease in trees and an increase in air pollution, causing several consequences. Environmental degradation is defined as the depletion of environmental resources such as air, water, and soil; the elimination of

ecosystems; extinction of wildlife; pollution perceived to be harmful to the ecosystem. Another factor for CO<sub>2</sub> is deforestation, which arises due to the excessive consumption and waste of paper products that come from the trees.

There are two ways to minimize the emission of CO<sub>2</sub>. First, fossil fuels can continue to be used with the recommendation to use different CO<sub>2</sub> capture, storage, and utilization methods. Second, people can switch to using alternative clean energies and biomaterials.<sup>6</sup> However, this way seems economically unviable as people cannot bear the high cost of such technologies. So, a combination of both can be a good option until new technologies are developed, Fig. 1.

### 3. Strategies for minimizing CO<sub>2</sub> emissions

The strategies that can be used to minimize anthropogenic CO<sub>2</sub> emissions include:<sup>7</sup>

(i) Decreasing the production of CO<sub>2</sub> with the use of the sources of renewable energy, such as solar, hydro, and wind, and by increasing energy efficiency.



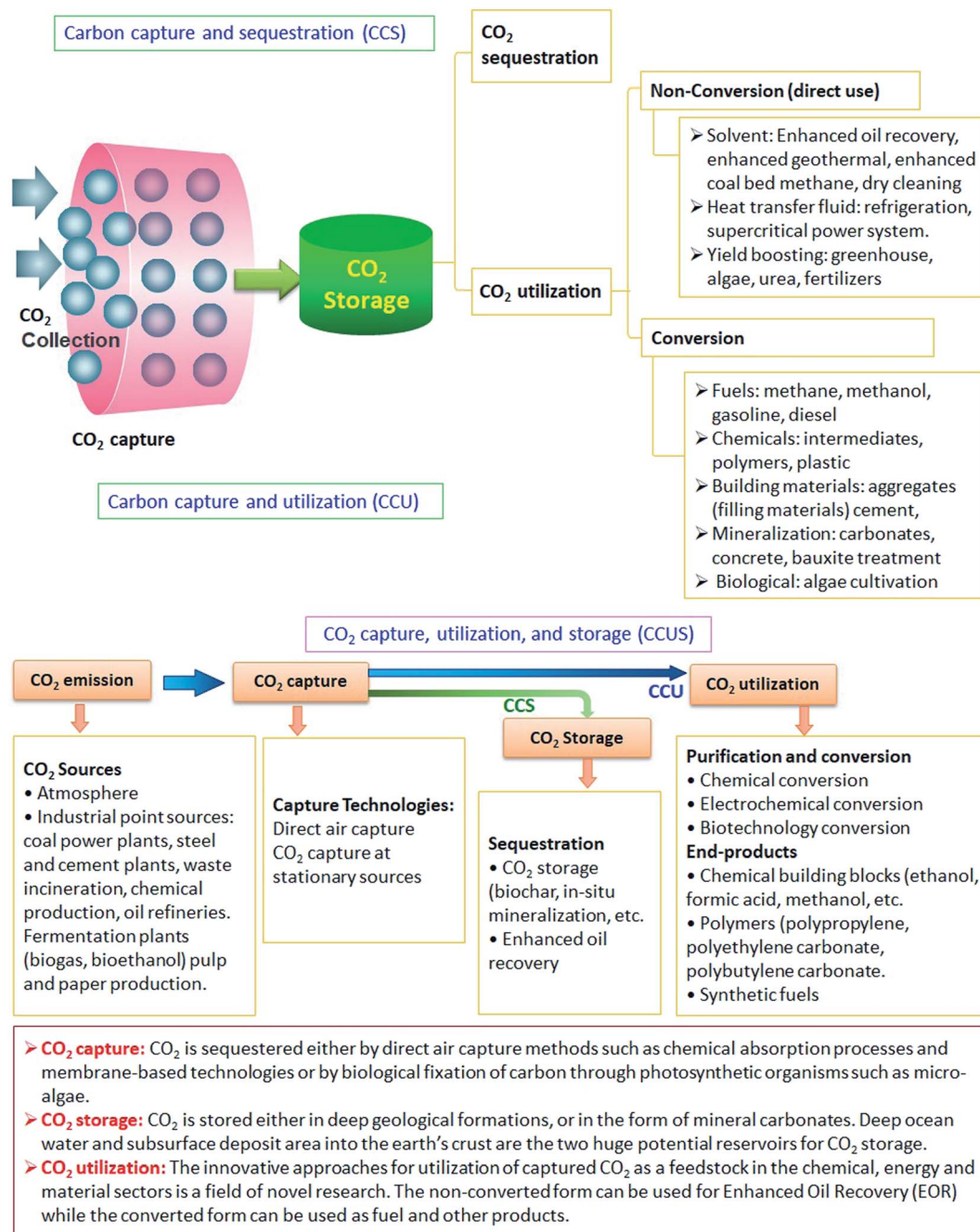


Fig. 2 Illustration of CO<sub>2</sub> steps of emission, capture, storage, and utilization.

(ii) Extracting produced CO<sub>2</sub> from the climate by reforestation and geological storage in deep-sea sediments and underground storage.

(iii) Converting and utilizing CO<sub>2</sub>.

In Fig. 2, several of the crucial procedures are displayed. The chemical sector, for example, has a growing demand for carbon, as does the desire to reduce its reliance on fossil fuels. This, combined with the desire to reach net-zero emissions in the future, has sped up feedstock development. As a result, the industry is aggressively developing carbon capture and utilization (CCU) technology to utilize CO<sub>2</sub> as a feedstock alongside

new generations of bio-based feedstocks and improved recycled raw materials. In recent years, several encouraging advancements have been made, and commercial items such as cosmetic Plastic Bottles manufactured from waste CO<sub>2</sub> are now accessible.

## 4. CO<sub>2</sub> sequestration

Carbon sequestration is capturing, securing, and storing CO<sub>2</sub> from the atmosphere. The goal is to prevent CO<sub>2</sub> from warming the atmosphere by stabilizing it in both solid and dissolved



forms. The method has great potential for cutting CO<sub>2</sub>. There are two basic forms of carbon sequestration; geological and biological.

Generally, sequestration can be done in three different ways: post-combustion capture, pre-combustion capture, and oxy-combustion. In addition, many other separation methods, such as gas phase separation, absorption into a liquid, and adsorption on a solid, as well as hybrid procedures like adsorption/membrane systems, are being researched. As companies move to restorative farming practices, they use the aforementioned procedures to collect the carbon emissions from power plants, factories, fuel-burning enterprises, and new generation animal production facilities.

Storage of CO<sub>2</sub> in vegetation, such as grasslands or forests, as well as in soils and oceans, is known as biological carbon sequestration. While the process of storing CO<sub>2</sub> in underground geologic formations, such as rocks, is known as geological carbon sequestration. Classically, CO<sub>2</sub> is extracted from an energy-related source, such as a power plant or a natural gas processing facility, or an industrial source, such as steel or cement production, and then injected into porous rocks for long-term storage. Carbon capture and storage may allow utilizing fossil fuels until another energy source is introduced on a large scale.

New ways of technological carbon sequestration are explored to remove and store CO<sub>2</sub> from the atmosphere using innovative technologies. Direct air capture of CO<sub>2</sub> can be done directly from the air using advanced technology plants. By developing novel types of chemicals that are capable of identifying and trapping carbon dioxide from the air, scientists are building molecules that can alter the shape. The engineered molecules act as a filter, only attracting CO<sub>2</sub>. It is highly of interest to have efficient methods for the CO<sub>2</sub> removal and utilization of a resource for several applications. This includes the use of CO<sub>2</sub> as a raw material to produce graphene.

## 5. CO<sub>2</sub> capture and separation technologies

Fig. 3 depicts the procedures and materials utilized for CO<sub>2</sub> capture and separation. Briefly, various methods were applied, including absorption, adsorption, separation, membrane, cryogenic distillation, chemical looping, and geothermal and biochemical technologies. CO<sub>2</sub> separation can be achieved by ionic liquid membranes, polymeric membranes, and MOF mixed matrix membranes. CO<sub>2</sub> capture can be achieved using biological separation/fixation techniques such as microalgae, bacteria, and their enzymes.

One of the main CO<sub>2</sub> separation technologies that can be applied to isolate the CO<sub>2</sub> from the fuel gas stream prior to transportation is absorption which can be done using liquid or solid sorbents. Liquid sorbents are absorbed to separate the CO<sub>2</sub> from the flue gas. The sorbent can be regenerated through a stripping or regenerative process by heating or depressurization. CO<sub>2</sub> absorption can be performed by common solvents, ionic liquids, deep eutectic solvents, phase-change ionic

liquids, solvents modified with nanoparticles, encapsulated liquid sorbents, novel gas-liquid contactors, and mini- and micro-channels, and rotating packed beds.

Adsorption using a solid sorbent binds the CO<sub>2</sub> on its surfaces. CO<sub>2</sub> adsorption can be performed by carbonaceous materials and nanomaterials, conventional and nanosized zeolites, functionalized sorbents, and swing technologies. Large specific surface area, high selectivity, and higher generation ability are the main criteria for sorbent selection. Another separation method is chemical looping combustion, in which a metal oxide is used as an oxygen carrier instead of using pure oxygen directly for the combustion, as in the case of oxyfuel combustion. During the process, the metal oxide is reduced to metal while the fuel is oxidized to CO<sub>2</sub> and water. In membrane separation, various membranes can allow only CO<sub>2</sub> to pass through, while excluding other flue gas components. Hydrate-based CO<sub>2</sub> separation is a new technology by which the exhaust gas containing CO<sub>2</sub> is exposed to water under high pressure forming hydrates. The CO<sub>2</sub> in the exhaust gas is selectively engaged in the hydrate cages and is separated from other gases. Cryogenic distillation is a gas separation process using distillation at very low temperatures and high pressure. It is similar to other conventional distillation processes except that it is used to separate components of gaseous instead of liquid. Many adsorption procedures are used to achieve CO<sub>2</sub> separation based on regeneration methods. This includes (1) vacuum as well as pressure swing adsorption (VSA and PSA), (2) temperature swing adsorption (TSA), (3) electric swing adsorption (ESA), (4) simulated moving beds (SMB), and (5) purge displacement.<sup>8,9</sup>

Organic cage frameworks (OCFs), pCage-1, and pCage-2 with controlled porosity synthesized from bicyclicoxacalixarene cages were reported to have high CO<sub>2</sub> adsorption capacities and adsorption selectivity of CO<sub>2</sub>/N<sub>2</sub>, that can be the reason for the introduction of N-doped triazine unit.<sup>10</sup> A cross-linked organo-magnesium complex (MTF-Mg) has been reported for selective CO<sub>2</sub> adsorption over N<sub>2</sub>.<sup>11</sup> The CO<sub>2</sub> preferential adsorption arises from its strong interaction with the exposed magnesium atoms.

In addition, porous organic polymer (HAT-TP) synthesized through a condensation reaction to introduce hexaaza-triphenylene (HAT) units to triptycene (TP)-based microporous polymer was reported as an effective recyclable catalyst for chemical conversions of CO<sub>2</sub> to cyclic carbonates with epoxide.<sup>12</sup>

In brief, CO<sub>2</sub> capture technologies include:

- Pre-combustion: in this process, the fuel is pretreated before combustion.
- Post-combustion: this process removes CO<sub>2</sub> from the flue gas after combustion.
- Oxyfuel combustion: in which oxygen, instead of air, is used for combustion.

Most promising capture technologies include capture at large point sources, which is the extraction of carbon dioxide from the flue gases of industrial sources (e.g., power plants, cement, or steel factories). Direct air capture requires more energy than direct capturing CO<sub>2</sub> in flue gases. In addition,



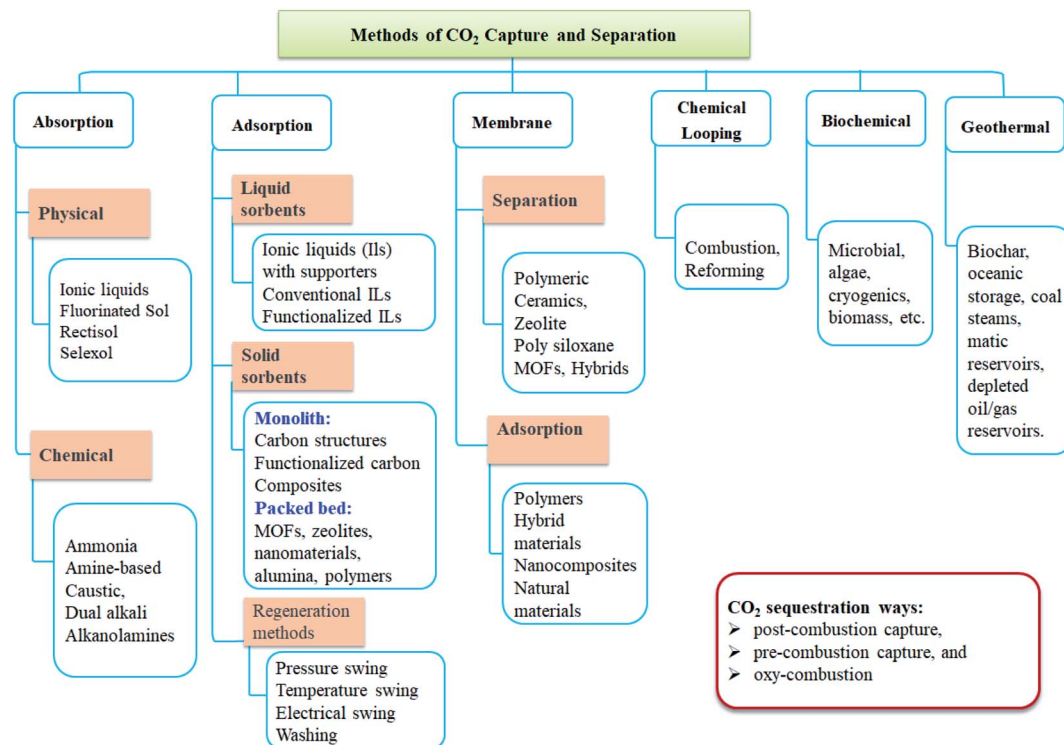


Fig. 3 Classification of CO<sub>2</sub> capture technologies.

capturing the CO<sub>2</sub> emitted by bioenergy production can reduce the atmospheric concentration of CO<sub>2</sub>. The general process is called bioenergy with carbon capture and sequestration.

## 6. CO<sub>2</sub> storage

The CO<sub>2</sub> capture and separation are followed by CO<sub>2</sub> transportation into the storage location. CO<sub>2</sub> storage is the last step in the CCS chain. CO<sub>2</sub> storage can be implemented in different modes classified into natural and man-made modes of storage. Natural modes include terrestrial sequestration, while man-made storage includes storage in geologic formations. The storage strategies include:

Oceanic underground geological storage is considered the most viable sequestration strategy. In comparison to carbonation and oceanic storage, geological storage is preferable due to several factors, including economic considerations, site accessibility (in the case of ocean and mineral sequestration), and associated worries about the security of the stored CO<sub>2</sub> and detrimental environmental effects of mineralization and ocean storage. There are several potential geological storage options, including saline aquifers, depleted oil and gas reservoirs, unmineable coal seams, basalt formations, organic-rich shales, hydrate storage of CO<sub>2</sub> within the subsurface environment, and CO<sub>2</sub>-based enhanced geothermal systems.

Deep ocean storage includes the CO<sub>2</sub> injection into deep ocean water. The main proposed approaches for ocean storage are based on the direct dissolution of CO<sub>2</sub> into the seawater.

Mineralization or mineral carbonation: in this strategy, the captured CO<sub>2</sub> is sequestered through the process of mineralization, where CO<sub>2</sub> is reacted with alkaline earth metal oxides or hydroxides, such as calcium- and magnesium-rich minerals, to produce stable carbonates.<sup>13</sup>

Terrestrial sequestration is the capture of CO<sub>2</sub> from the atmosphere and storing of it in soils and vegetation. CO<sub>2</sub> removal from the atmosphere through photosynthesis and prevention of the emission of CO<sub>2</sub> from terrestrial sources are the mechanisms for terrestrial storage.<sup>14</sup>

## 7. CO<sub>2</sub> utilization

The scientific community opposes CO<sub>2</sub> capture and storage (CCS) because of long-term liability matters, limited cost-effective storage capacity, the probability of leakage, and public acceptance of onshore storage locations.<sup>15</sup> At the same time, deep ocean sequestration would instantly influence lowering pH, enhancing water acidity, and potentially causing ecosystem imbalance.<sup>16</sup>

Carbon capture and utilization (CCU) is a viable alternative to CCS that is gaining traction owing to sustainable progress and is thought to be a long-term solution to the CO<sub>2</sub> problems. CCU explores the use of CO<sub>2</sub> in applications other than storage. CO<sub>2</sub> is a vital raw material for products that continue to require carbon sources. This is because it provides their structure and properties (carbon-containing chemicals). Another reason is using carbon-free energy carriers, such as electricity or hydrogen. CO<sub>2</sub> is one of the few carbon alternative sources to



fossil fuels. The chemical feedstocks,<sup>17</sup> refrigerants,<sup>18</sup> cleaning liquids,<sup>19</sup> solvents media,<sup>20,21</sup> inserting agents, and packing gas are examples of CO<sub>2</sub> use attempts that have been demonstrated in recent years.

CO<sub>2</sub> utilization can be classified into non-conversion utilization (direct use) and conversion utilization, Fig. 4. The entire CCU process can be broken down into two steps:

- The initial step in CCU is the capture of CO<sub>2</sub> and separation at the production source.
- The next step is CO<sub>2</sub> utilization performed by (i) non-conversion process to use CO<sub>2</sub> as a solvent, a working fluid, and a heat transfer agent or by (ii) conversion process to use it as a feedstock for the production of fuels, chemicals, and polymers, Fig. 3. The advantages and disadvantages of some of the potential technological ways of CO<sub>2</sub> use are listed in Table 1.

### 7.1. CO<sub>2</sub> non-conversion utilization (direct use)

CO<sub>2</sub> can be used directly in several applications such as dry ice, carbonated drinks, fire extinguisher, solvent, refrigerants, process fluids, welding mediums, or in algae farms for photosynthesis. It can also be used in large-scale industries to enhance oil recovery, gas recovery, and geothermal systems indirectly. Also, the direct use of CO<sub>2</sub> includes its use as heat transfer fluid in refrigeration, power systems, and other industries. Another example of CO<sub>2</sub> non-conversion utilization is in desalination, where CO<sub>2</sub> is combined with brine at high temperature and pressure, forming hydrates, which may then be extracted to reveal clean water.

In such uses, CO<sub>2</sub> molecules remain pure or dissolved in a mixture and do not react or crack further. However, such direct applications for CO<sub>2</sub> are limited in scale and have a small effect on the overall CO<sub>2</sub> abatement.<sup>22</sup>

### 7.2. CO<sub>2</sub> conversion utilization

A potential solution to environmental issues like global warming and the energy crisis is the conversion of CO<sub>2</sub> to sustainable and green solar fuel. Technologies like CO<sub>2</sub> capture, storage, and usage provide appealing methods to lower CO<sub>2</sub> emissions. Although CO<sub>2</sub> can be effectively separated *via* CO<sub>2</sub> collection and storage, converting CO<sub>2</sub> into chemicals and fuels is more practical. It converts CO<sub>2</sub> into crucial molecules like carbonate, methanol, salicylic acid, and other substances.

In the conversion process, a carbon-carbon bond or a carbon-hydrogen bond has to be established. Such bond formation requires energy input to activate CO<sub>2</sub> or the other substrates such as reductive coupling. Inappropriately, the carbon-oxygen double bond is very stable (energy of CO<sub>2</sub> 750 kJ mol<sup>-1</sup>) compared with C-H and C-C chemical bonds (430 and 336 kJ mol<sup>-1</sup>). Commonly, chemical fixation of CO<sub>2</sub> requires: (i) high input of energy to perform reaction activity of substrate (unsaturated compounds, small-ring compounds, and organometallic compounds) and (ii) high reaction temperature and pressure. There are several pathways for CO<sub>2</sub> conversion. These can be classified as shown in Fig. 5.

In brief, the CO<sub>2</sub> conversion reactions can be categorized into two classes:

(i) The first class includes the reactions that do not need a substantial amount of external energy. Hence, the reaction occurs by attaching the CO<sub>2</sub> molecule to the other reactant. These reactions are usually called carboxylation reactions. Consequently, this class involves the production of carboxylates and lactones (RCOOR), carbamates (R<sub>1</sub>R<sub>2</sub>NCOOR<sub>3</sub>), ureas (RRNCONRR), isocyanates (RNCO), and carbonates (ROC(O)OR).

(ii) The second class includes the reactions that produce reduced forms of CO<sub>2</sub>. Such reduction reactions require a significant amount of external energy. They involve products including; HCOO<sup>-</sup> (formates), [C(O)O]<sub>2</sub><sup>2-</sup> (oxalates), H<sub>2</sub>CO (formaldehyde), CO, CH<sub>3</sub>OH, CH<sub>4</sub>, and C<sub>2</sub>H<sub>4</sub>. The external energy needed in these reactions is supplied as heat, electrons, or irradiation/photons to break the bonds in CO<sub>2</sub>. Such processes are named thermal, electrochemical, and photochemical, respectively. Consequently, catalysis, and high temperature and pressure, are required for lowering the energy barrier toward the formation of C1-building block chemicals, for instance.<sup>23,24</sup>

Such catalytic process of CO<sub>2</sub> includes the formation of chemicals such as urea, methane, methanol, formic acid, formaldehyde, ethylene carbonate, dimethyl carbonate, cyclic carbonates, salicylic acid, cyclic carbonates, polymer building blocks, and polycarbonates.

**7.2.1. CO<sub>2</sub> thermal conversion.** Thermochemical conversion of CO<sub>2</sub> utilizes catalysts and a combination of heat and pressure to convert CO<sub>2</sub> into valuable products. However, the reversibility of reactions and thermodynamic restrictions on reactions are obstacles to this method. In contrast to procedures like catalytic hydrogenation for the synthesis of methanol, which is created to be decentralized to take advantage of point sources of CO<sub>2</sub>, methods like Fischer-Tropsch are developed in large-scale factories to maximize economies of scale. An example is the reverse water gas shift to convert CO<sub>2</sub> and H<sub>2</sub> to CO and H<sub>2</sub>O. It may be followed by other processes such as Fischer-Tropsch to produce liquid synthetic fuels such as e-diesel, e-gasoline, and e-kerosene.

**7.2.2. CO<sub>2</sub> electrochemical conversion.** In electrochemical CO<sub>2</sub>, electricity is applied to induce a nonspontaneous reaction of CO<sub>2</sub> reduction. This is similar to water electrolysis for green hydrogen production when the electricity is from a renewable source. Electrolysis is performed at low or high temperatures. The low temperature is more flexible but less energy efficient. High-temperature electrolysis is performed in solid oxide electrolyzer cells and is used to reduce CO<sub>2</sub> into C1 products such as CO or its mixture with hydrogen (syngas). CO<sub>2</sub> is split into CO and O<sub>2</sub>, and the process is performed in the gaseous phase at 600–800 °C. With a low-temperature reduction of CO<sub>2</sub>, C2+ products such as ethanol, ethylene, and propylene can be produced using an aqueous electrolyte design or membrane electrode assembly.

In bioelectrochemical processes, CO<sub>2</sub> is converted with the support of microorganisms directly in one step. However, it can also be converted with separate production of H<sub>2</sub> in a two-step process. In the first step, hydrogen is produced, then in the second step, hydrogen and CO<sub>2</sub> are fed to a bioreactor



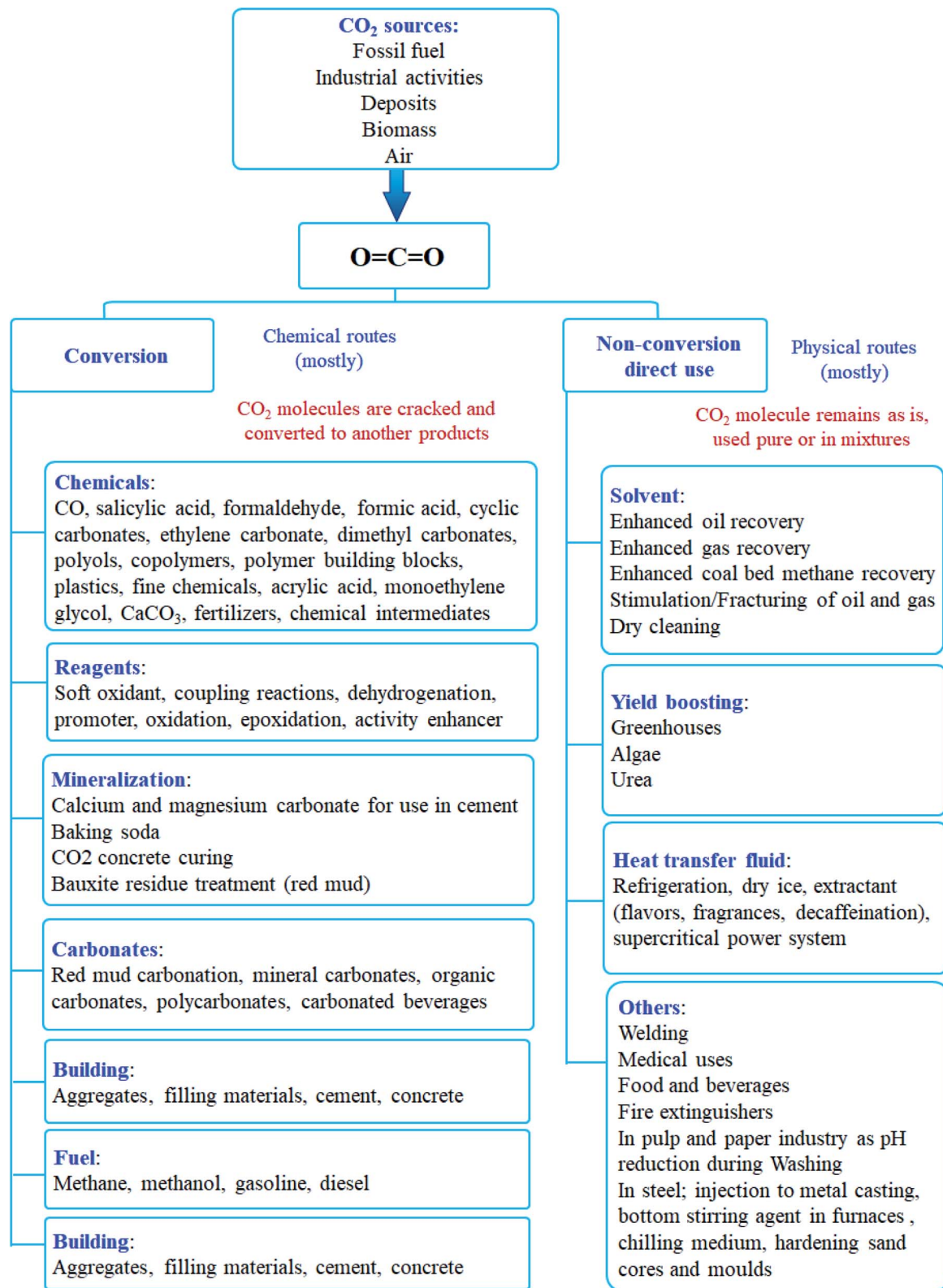


Fig. 4 Classification of CO<sub>2</sub> utilization in various fields and industries.

containing anaerobic methanogenic species for methane production.

**7.2.3. CO<sub>2</sub> bio-chemical/enzymatic conversion.** CO<sub>2</sub> contains carbon, which is the major component of biofuels.

Therefore, CO<sub>2</sub> can be turned into biofuels and bioenergy, making it a potential candidate for renewable energy production. In bioconversion to energy, CO<sub>2</sub> is first captured into a biological system, and then converted into biofuels or



Table 1 Potential technological ways of CO<sub>2</sub> uses

Technology	Description	Advantages	Disadvantages
<b>(i) Non-conversion</b>			
Desalination	CO <sub>2</sub> is combined with brine at high temperature and pressure forming hydrates, which may then be extracted to reveal clean water	<ul style="list-style-type: none"> <li>&gt; Produces potable water or treats water that has been contaminated by a procedure</li> <li>&gt; Enables a revenue stream or cost offset in a system that has already committed to CCS</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Costs of power and equipment, however, similar to existing water treatment substitutes</li> </ul>
Enhanced oil recovery	CO <sub>2</sub> is pumped into existing oil wells to boost pressure and reduce oil viscosity, allowing for more oil to be retrieved	<ul style="list-style-type: none"> <li>&gt; It is a mature technology with permanent storage and a great potential for CO<sub>2</sub> utilization, as well as an income source to pay the costs of carbon capture</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Facilitates further fossil fuel use, producing more CO<sub>2</sub></li> </ul>
Enhanced geothermal systems	Supercritical CO <sub>2</sub> is used to transmit geothermal heat or to create electricity directly using a supercritical CO <sub>2</sub> turbine	<ul style="list-style-type: none"> <li>&gt; Improves the efficiency of a renewable energy source and</li> <li>&gt; Provides long-term storage</li> </ul>	<ul style="list-style-type: none"> <li>&gt; It takes a long time for a product to be commercialized</li> <li>&gt; Transporting supercritical CO<sub>2</sub> is expensive</li> <li>&gt; A geothermal site requires a grid connection</li> </ul>
Enhanced coal bed methane	CO <sub>2</sub> is pumped into partially depleted coal seams, where it is absorbed by coal, causing methane to be displaced to the surface, where it can be recovered and used as a fuel	<ul style="list-style-type: none"> <li>&gt; Methane may replace more carbon-intensive fuel sources</li> <li>&gt; It is with permanent storage</li> </ul>	<ul style="list-style-type: none"> <li>&gt; CO<sub>2</sub> adsorbed in coal might cause it to swell and impede routes, causing methane recovery to be hampered</li> <li>&gt; A low cost of methane</li> <li>&gt; CO<sub>2</sub> transportation costs</li> </ul>
<b>(ii) Conversion</b>			
<i>Mineralization</i>			
CO <sub>2</sub> mineralization	CO <sub>2</sub> reacts with minerals or industrial waste products. This results in new compounds utilized in constructions, as consumer products, or as a substitute to CCS	<ul style="list-style-type: none"> <li>&gt; Abundant materials (minerals or industrial wastes)</li> <li>&gt; Substitute to CCS</li> </ul>	<ul style="list-style-type: none"> <li>&gt; To speed up the process, high energy is used</li> <li>&gt; High material requirements</li> <li>&gt; Minerals and processing costs</li> </ul>
Concrete curing	Precast concrete is cured using waste CO <sub>2</sub> flue gas. CO <sub>2</sub> is kept in the concrete as a non-reactive limestone	<ul style="list-style-type: none"> <li>&gt; Low cost <i>versus</i> traditional curing</li> <li>&gt; Flue gases can be used directly in the cement industry</li> <li>&gt; Carbon offset opportunity for the cement industry, which produces a lot of pollution</li> <li>&gt; A low-carbon consumer item that has the potential to grow beyond its current market</li> </ul>	<ul style="list-style-type: none"> <li>&gt; The product must meet quality requirements</li> <li>&gt; The expense of modifying the curing process</li> </ul>
Bauxite residue carbonation	The alkalinity of aluminum mining slurry is reduced by CO <sub>2</sub>	<ul style="list-style-type: none"> <li>&gt; Aluminum mine closure and reclamation expenses can be reduced</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Cost of concentrating CO<sub>2</sub></li> <li>&gt; Need access to CO<sub>2</sub></li> </ul>
<i>Biological</i>			
Algae cultivation	CO <sub>2</sub> is absorbed by microalgae, which can then be transformed into proteins, fertilizers, and biomass for biofuels	<ul style="list-style-type: none"> <li>&gt; Competitive source of biofuel</li> <li>&gt; Can use flue gas directly</li> <li>&gt; Can result in permanent storage</li> <li>&gt; A tonne of microalgae can fix about two tonnes of CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>&gt; Algae are sensitive to impurities, pH</li> <li>&gt; Cost of controlling growth and drying conditions</li> <li>&gt; Large area and sunny climate needed for ponds</li> <li>&gt; High energy needs for photobioreactors</li> </ul>
<i>Chemicals</i>			
Liquid fuels – methanol	Methanol is produced by catalytically converting CO <sub>2</sub> and hydrogen into methanol, which can be combined with gasoline	<ul style="list-style-type: none"> <li>&gt; The energy carrier eventually replaces fossil fuels, lessening our reliance on them for transportation and other purposes</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Inefficient process; requires renewable or low emissions energy to have net CO<sub>2</sub> abatement benefit</li> <li>&gt; Needs low-cost renewable hydrogen</li> <li>&gt; Cost of purifying CO<sub>2</sub></li> </ul>
Liquid fuels – formic acid	Formic acid is made by electro-reducing CO <sub>2</sub> in water	<ul style="list-style-type: none"> <li>&gt; Formic acid is a preservative and antibacterial agent that can be utilized as an energy carrier (with hydrogen as the major fuel)</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Inefficient process; requires renewable or low emissions energy to have net CO<sub>2</sub> abatement benefit</li> <li>&gt; Chemistry needs to be perfected</li> <li>&gt; Cost of purifying CO<sub>2</sub></li> </ul>



Table 1 (Contd.)

Technology	Description	Advantages	Disadvantages
Polymers/chemical feedstock	CO <sub>2</sub> is converted into polycarbonates with the use of a zinc-based catalyst	<ul style="list-style-type: none"> <li>&gt; Flue gas can be used directly; CO<sub>2</sub> has a significant potential usage; a wide range of products (plastic bags, laminates, automobiles, medical components, and so on) are possible</li> <li>&gt; Existing infrastructure can be employed</li> </ul>	<ul style="list-style-type: none"> <li>&gt; Non-permanent storage; some CO<sub>2</sub> can be re-emitted as soon as six months</li> </ul>
Urea yield boosting	Urea fertilizer is made from ammonia and CO <sub>2</sub>	<ul style="list-style-type: none"> <li>&gt; Process emissions intensity is reduced</li> </ul>	<ul style="list-style-type: none"> <li>&gt; CO<sub>2</sub> is re-emitted when urea is broken down as fertilizer</li> <li>&gt; Non-permanent storage</li> </ul>

bioenergy. Engineered microbes convert CO<sub>2</sub> into value-added bio-based chemicals.<sup>25</sup>

Due to the limitations of natural CO<sub>2</sub> fixing pathways, synthetic CO<sub>2</sub> fixation routes have been developed at levels of *in silico* prediction, *in vitro* testing, and *in vivo* implantation of a synthetic CO<sub>2</sub> fixation pathway. Multiple criteria are considered while designing a synthetic CO<sub>2</sub> fixing pathway. Oxygen-tolerant and kinetically fast carboxylases are considered to incorporate into the pathways. The undesired side reactions are kept at a minimum. After passing the topological, energetic, and kinetic assessment, the resulting designed pathway is anticipated to have quick overall pathway kinetics, high flux, and improved performance compared to natural CO<sub>2</sub> fixing pathways.

The photosynthetic recycling of CO<sub>2</sub> can be used to produce products such as 2-methyl-1-butanol, isobutyraldehyde, and isobutanol, ethanol, butanol, malate, formate, lipids, sugars (hexose, pentose, and triose), biomass, succinate, limonene, isopropanol, acetic acid, isobutanol, and 3-methyl-1-butanol, succinic acid, isobutyraldehyde, 1,3-propanediol.<sup>26</sup>

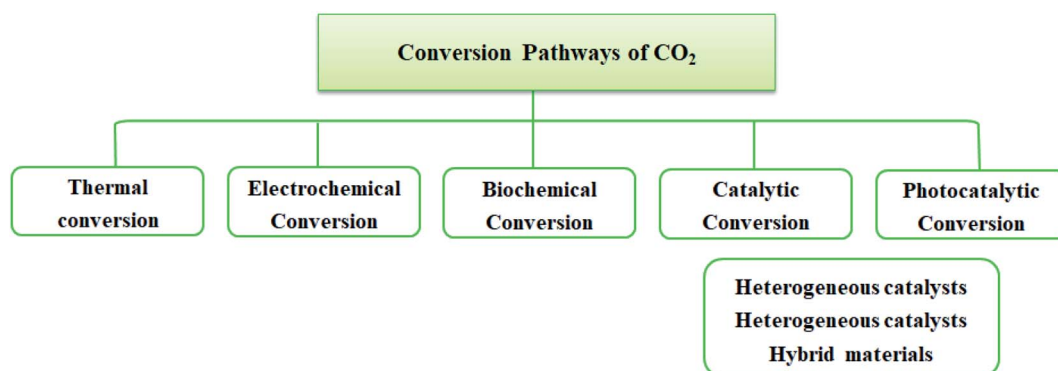
**7.2.4. CO<sub>2</sub> catalytic conversion.** The catalytic conversion of CO<sub>2</sub> into chemicals is of high interest. Both homogeneous and heterogeneous catalysis processes can be used. Valuable chemicals such as carbonates, carbamates, urethanes, lactones, pyrones, and formic acid and their derivatives can be synthesized by homogeneous catalysts. Heterogeneous catalysis can offer several technical advantages such as stability, separation, handling, and reusing of the catalyst and reactor design. Although CO<sub>2</sub> activation by heterogeneous catalytic routes is

still limited, efforts have been made toward synthesizing dimethyl carbonate, cyclic carbonates, and synthetic gas (CO, H<sub>2</sub>) and methanol synthesis from CO<sub>2</sub> hydrogenation.<sup>27</sup>

Examples of CO<sub>2</sub> catalytic conversion include CO<sub>2</sub> reforming of CH<sub>4</sub>, CO<sub>2</sub> hydrogenation to methanol, formation of dimethyl carbonate from CO<sub>2</sub> and methanol, formation of cyclic carbonate from CO<sub>2</sub> and epoxide, and formation of cyclic carbonate from CO<sub>2</sub> in the presence of ammonium salt, and the reaction of CO<sub>2</sub> and propylene glycol.<sup>28</sup>

Catalytic conversion of CO<sub>2</sub> can be used to form hydrocarbon and non-hydrocarbon fuels. Because of the high stability of CO<sub>2</sub> molecule ( $\Delta G_f^\circ = -396 \text{ kJ mol}^{-1}$ ), CO<sub>2</sub> conversion into valuable products requires high energy depending on the downward steps for 4+ oxidation state of carbon. CO<sub>2</sub> conversion to HC fuels involves a high energy process, where the C-oxidation state is +2 or lower for possible production of compounds such as HCOOH, H<sub>2</sub>CO, CH<sub>3</sub>OH, CH<sub>4</sub>, and other HCs.<sup>29</sup>

There are two ways to convert CO<sub>2</sub> into hydrocarbon-based fuels; (1) transformation using classical Fischer-Tropsch synthesis [Ramirez] through reverse water-gas shift (RWGS) reaction followed by HC cracking, isomerization and aromatization, (2) CO<sub>2</sub> transformation into methanol (MeOH) followed by the MeOH conversion to HC. The CO<sub>2</sub> is first converted *via* the Fischer-Tropsch synthesis and then followed by coupling with the Fischer-Tropsch catalyst system containing zeolite. This is to allow production distribution and selectivity to olefins and or aromatic. Similarly, combining the CO<sub>2</sub> with MeOH catalyst system, *i.e.*, zeolite, can also allow the generation of useful chemicals *via* the CO hydrogenation.<sup>30</sup>

Fig. 5 Conversion strategies of CO<sub>2</sub>.

Catalysts such as metals and their oxides, carbon nanostructures, metal–organic frameworks (MOFs), and polymer functionalized materials have been reported for CO<sub>2</sub> conversions.<sup>31</sup> For CO<sub>2</sub> reduction, the one-electron reduction is endothermic and produced (CO<sub>2</sub><sup>•−</sup>) is highly reactive. Electrochemical potentials of possible CO<sub>2</sub> reduction reactions in aqueous solutions for the production of different chemicals and hydrocarbon fuels are in equations:

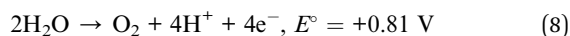
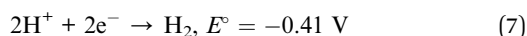
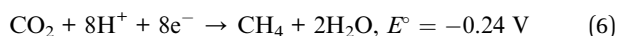
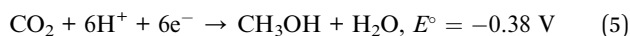
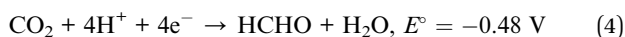
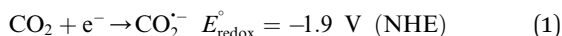


Fig. 6 lists several reactions for the transformation of CO<sub>2</sub> into products that are commercially valuable.<sup>32</sup>

**7.2.4.1. Nanomaterials used for CO<sub>2</sub> catalytic conversion.** The general classification of the materials and nanomaterials used for CO<sub>2</sub> conversion can be listed in Fig. 7. These materials can be prepared, modified, and used individually or prepared in a hybrid or combination of two or more chemicals. Hybridization of two or more types of these materials may further improve efficiency. For example, carbon materials like graphene, graphene oxide (GO), reduced GO, carbon nanotubes, and graphitic carbon nitride (g-C<sub>3</sub>N<sub>4</sub>) are commonly used for CO<sub>2</sub> applications. By varying the precursor, performing post-synthetic functionalization, and modification with metal nanoparticles or polymeric branches, the electronic band structures of the carbon nanomaterials and their light absorption features can be tuned, therefore, enhancing the CO<sub>2</sub> conversion and making them attractive for CO<sub>2</sub> applications.<sup>33–35</sup>

Solid substrates are functionalized or modified with amines and ionic liquids<sup>36,37</sup> to have more affinity toward CO<sub>2</sub>. Nevertheless, polymers such as amidine and guanidine-based polymers, poly(ethylene-imine), poly(ether imide), and poly(ionic liquid)s (PILs) interact more with CO<sub>2</sub>.<sup>38</sup> Other polymers, including polystyrene, polysulfone, or poly(ether-*b*-amide-6), can be utilized due to their controllable porosity, good CO<sub>2</sub> permeability, and selectivity.

Porous organic polymers prepared from specific multi-dentate organic building blocks are good candidates for CO<sub>2</sub> applications.<sup>39,40</sup> However, polymerization conditions play a key role in their porosity. In addition, cross-linking of polymers is optimized and controlled to get macroporous (>50 nm), mesoporous (2–50 nm), and microporous (<2 nm) materials. This can

also impact the pore volume and surface area, which are important parameters affecting the affinity toward CO<sub>2</sub>.<sup>41</sup>

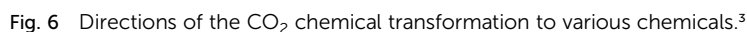
Another class of materials is the inorganic materials which can be synthesized with good morphology and high surface area. Examples include spherical nanoparticles, nanowires, nanocubes, and nanosheets. These materials can be easily prepared with controlled properties. For instance, nanoparticles of numerous shapes display various efficiencies for identical catalytic processes owing to the exposure of several crystal facets.<sup>42–44</sup> Metal such as palladium, gold, silver, and copper are the most efficient. With the ability to stabilize the reaction intermediates, metals such as copper are outstandingly active for CO<sub>2</sub> reduction to hydrocarbons. However, in some cases, palladium, gold, and silver form CO.<sup>45,46</sup> MOFs are another class of materials that showed excellent performance in CO<sub>2</sub> applications owing to their crystallinity and high surface area.<sup>47,48</sup> Such materials with crystals show high internal cavities interconnected mainly by small channels to play a key role in several CO<sub>2</sub> applications.<sup>49,50</sup> Heterogeneous catalytic conversion of CO<sub>2</sub> to chemicals and fuels is gaining particular interest because of its better stability, durability, simplicity in separation, handling, and simpler reactor design.

**7.2.4.2. Homogeneous and heterogeneous metal complex-based catalysts.** Homogeneous and heterogeneous metal complex-based catalysts are used for the electroreduction of CO<sub>2</sub>, Fig. 8. In homogeneous catalysis, the metal complex acts as a redox shuttle between the electrode and CO<sub>2</sub>. Mostly, the catalyst is in a more highly reduced state due to its acceptance of electrons from the electrode. As a result of the reduction, the catalyst transfers electrons to CO<sub>2</sub> in the solution and returns to its initial state, resulting in an indirect electrolysis reaction.<sup>31</sup> Catalysts are often single atom transition-metal complexes stabilized by ligands in environments that tune the redox potentials of the catalyst. In the stable coordination environments found for typical Ir and Ru metal complexes, there is often a high catalytic selectivity after optimization in the design of the catalyst. However, the difficulties of catalyst recovery after catalytic cycles with considerable energy demands from distillation, filtration, or crystallization to recover the catalyst is a significant impediment in large-scale synthesis.

Catalyst immobilization in surface or electrochemical reactions combines the benefits of homogenous catalysis and selectivity with the capacity to reuse the catalysts. With the reduction of CO<sub>2</sub> as our primary goal, we devised many techniques, including polymerization, noncovalent surface binding, and surface-chemical binding, to make chemically modified electrodes.<sup>51</sup> Surface binding facilitates electron transfer from the electrode to metal complex catalysts on the surface. The electrochemical reduction of CO<sub>2</sub> using heterogeneous catalysts with high surface area is an appealing method. Nanostructured catalysts can produce much improved reactive surfaces with a significant portion of the reactive sites available for catalysis compared to traditional electrodes.

**7.2.5. CO<sub>2</sub> photocatalytic conversion.** Photocatalytic systems can potentially conduct difficult transformations, which thermal reactions cannot realize. Several materials and nanomaterials used as photocatalysts have been tested to





**7.2.5.1. Photocatalysts requirements.** Catalysts should be with: (i) photosensitizer component (to initiate photochemical one-electron transfer), such as organic compounds semiconductors and metal complexes, and (ii) catalyst (to convert one-electron transfer into a multi-electron reduction of  $\text{CO}_2$ ), such as complexes, metal particles, and enzymes. Excellently designed photocatalysts (rhenium(i) complexes) can fill both roles. The photocatalytic efficiency can be evaluated by: (i) product selectivity, (ii) quantum yield = (product/mol)/(absorbed photons/einstein), (iii) the stability of the

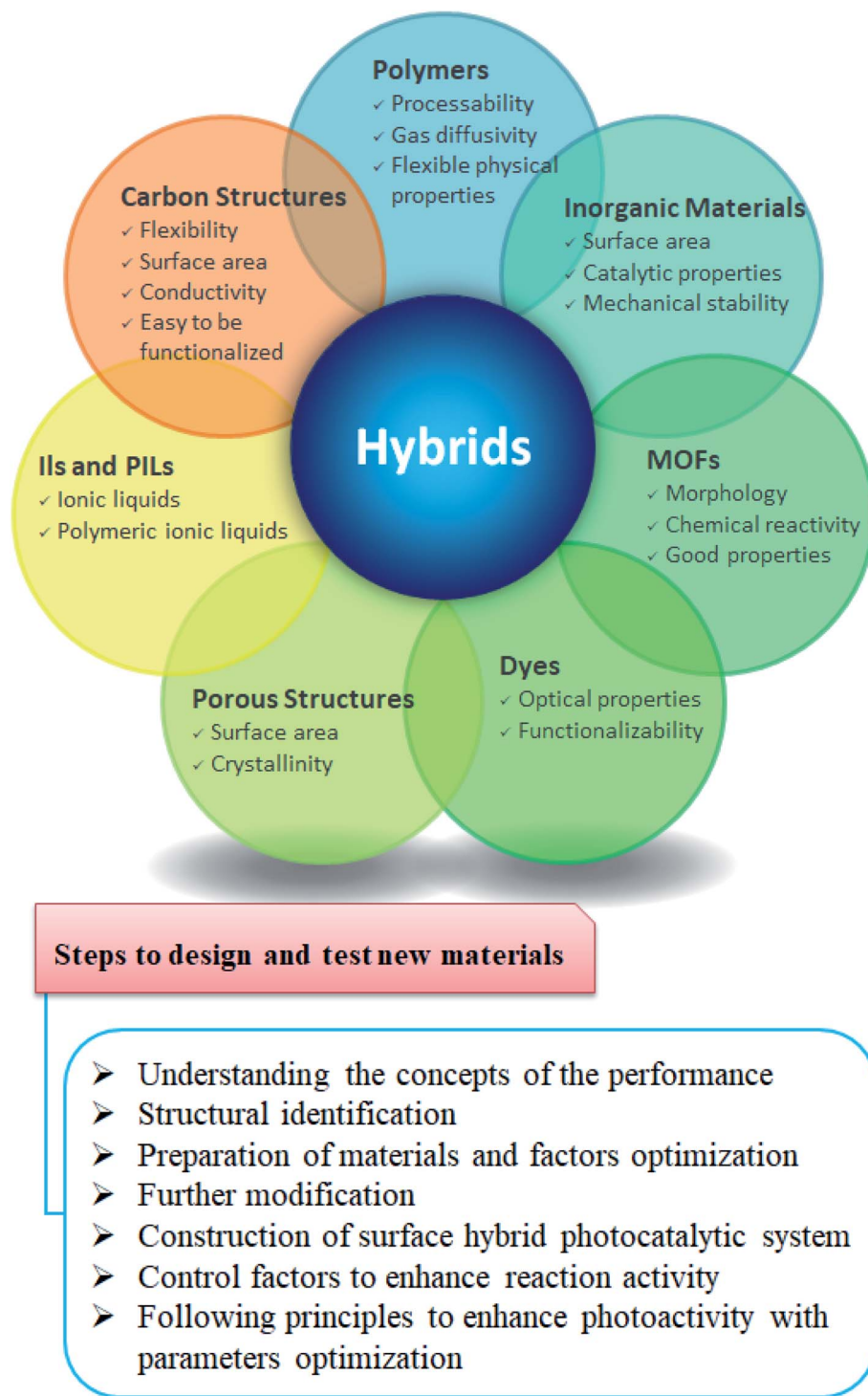


Fig. 7 Examples of building blocks that form hybrid materials for CO<sub>2</sub> application.

photocatalyst given by turnover number (TON) = (product/mol)/(photocatalyst/mol or unit mass), (iv) the photocatalytic cycle speed given by turnover frequencies (TOF) = TON/(reaction time/min).

**7.2.5.2. Homogeneous catalysts.** Homogenous redox photocatalysts consist of a light-harvesting unit (photosensitizer) and two catalytic sites. One site is for the oxidation process, where

a donor provides the electrons, and the other is the reduction site, where the electrons are transferred to an acceptor. Sometimes, the photosensitizer works as photosensitizer and reduction site.<sup>66</sup>

Visible light absorption by the photosensitizer unit leads to the excited state. Commonly used photosensitizers for CO<sub>2</sub> reduction are ruthenium (polypyridyl)- and (bipyridyl)-



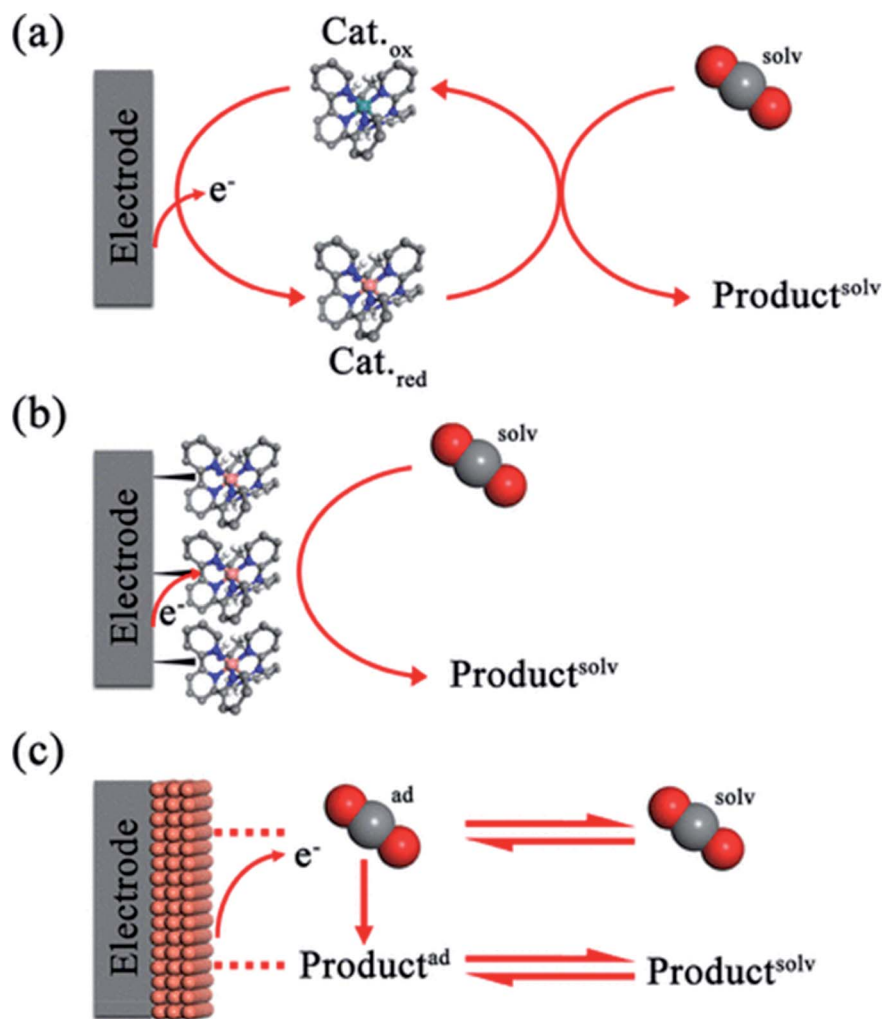


Fig. 8 Reduction of  $\text{CO}_2$  by various catalytic mechanisms: (a) homogeneous, (b) immobilized, and (c) heterogeneous way in an electrocatalytic film.<sup>52</sup>

rhodium(i) complexes (2.1 Chromophores). So, the light absorption gives rise to a single metal to ligand charge transfer ( $^1\text{MLCT}$ ), which produces a triplet excited state ( $^3\text{MLCT}$ ) by inter-system crossing. This  $^3\text{MLCT}$  state has different redox properties than the ground state. Owing to this state's reducing properties, direct interaction with an acceptor can lead to the one-electron oxidized ground state of the photosensitizer *via* oxidative quenching. In terms of  $\text{CO}_2$  reduction, reductive quenching is the more important process. With an electron from the oxidation site, a ground state of electron reduced species is formed, capable of transferring electron to the reduction site to recover the  $d^6$  neutral ground state of the photosensitizer.<sup>67</sup>

When exposed to light radiations of suitable frequencies, the ruthenium- or iridium-based complexes convert  $\text{CO}_2$  into CO or formate.<sup>4</sup> A series of anthracene-substituted mononuclear and dinuclear rhodium complexes have been reported for photocatalytic  $\text{CO}_2$  reduction showing a good TON value and long life.<sup>5</sup> The anthracene moiety also functions as a sterically bulky

group that may inhibit deleterious intermolecular catalyst deactivation pathways.

Examples of the multi-component system include ruthenium(i) diimine photosensitizers, rhodium(ii) diimine, photosensitizer, and organic photosensitizers.<sup>41</sup> Moreover, some supramolecular photocatalysts are also used, such as  $\text{Ru(II)-Ni(I)}$ ,  $\text{Ru(II)-Co(III)}$ , and  $\text{Ru(II)-Re(I)}$ . An example of the selective catalytic reduction site for the photoreduction of  $\text{CO}_2$  over rhodium(i) systems is given in Fig. 10.<sup>28</sup>

**7.2.5.3. Heterogeneous catalysts.** Several heterogeneous catalysts have been developed, including metal-supported catalysts, perovskites, and solid solution catalysts.<sup>69</sup> The heterogeneous catalyst consists of metal, supports, and promoters. Precious metals (Pt, Rh, or Ru) are known to have high activity and durability and are resistant to coke deposition, although at a high price. The precious metal-based catalysts show high activity in spite of the very small amount of metal catalyst used.

Non-precious metals (Ni or Co) have been widely investigated as well. Non-precious metals such as Ni or Co have been used



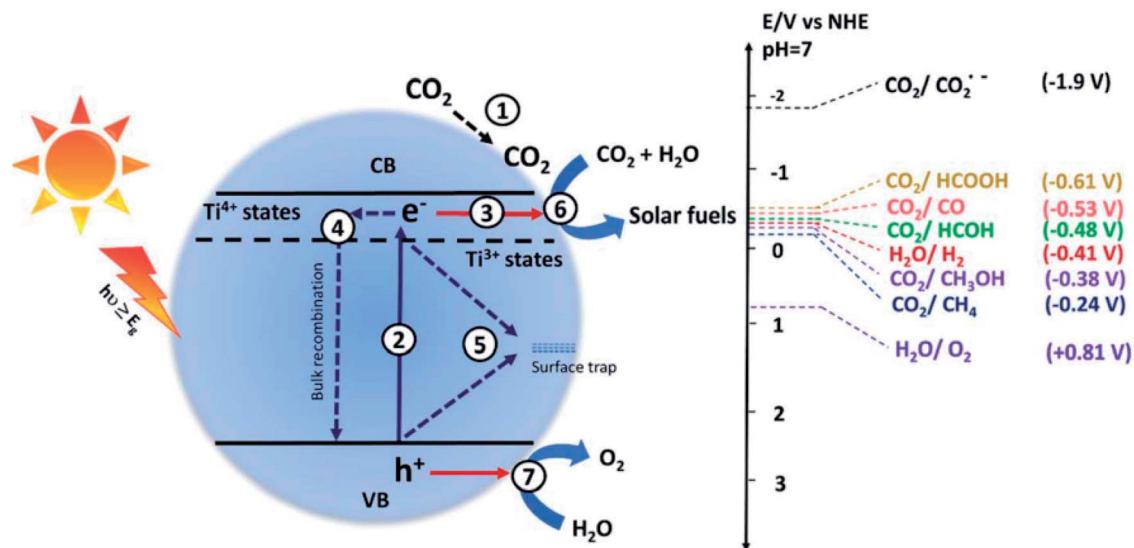


Fig. 9 Steps of photocatalytic CO<sub>2</sub> conversion. The absorption of light energy equal to or greater than the bandgap ( $E_g$ ) results in the excitation of the electrons from the valence band (VB) to the conduction band (CB), leaving behind holes in the VB. The electrons and holes promote the reduction and oxidation of the reactant molecules.<sup>53</sup>

more for DRM due to their low price and abundance.<sup>70</sup> Ni catalysts have shown a level of activity comparable to precious metals. Alloyed metal catalysts are widely used because they have a different electronic structure than monometallic

materials. Monometallic Ni or Fe catalysts have shown poor durability because the monometallic Ni catalyst is easily deactivated by coke deposition, and Fe is not much active for CO<sub>2</sub> conversion.

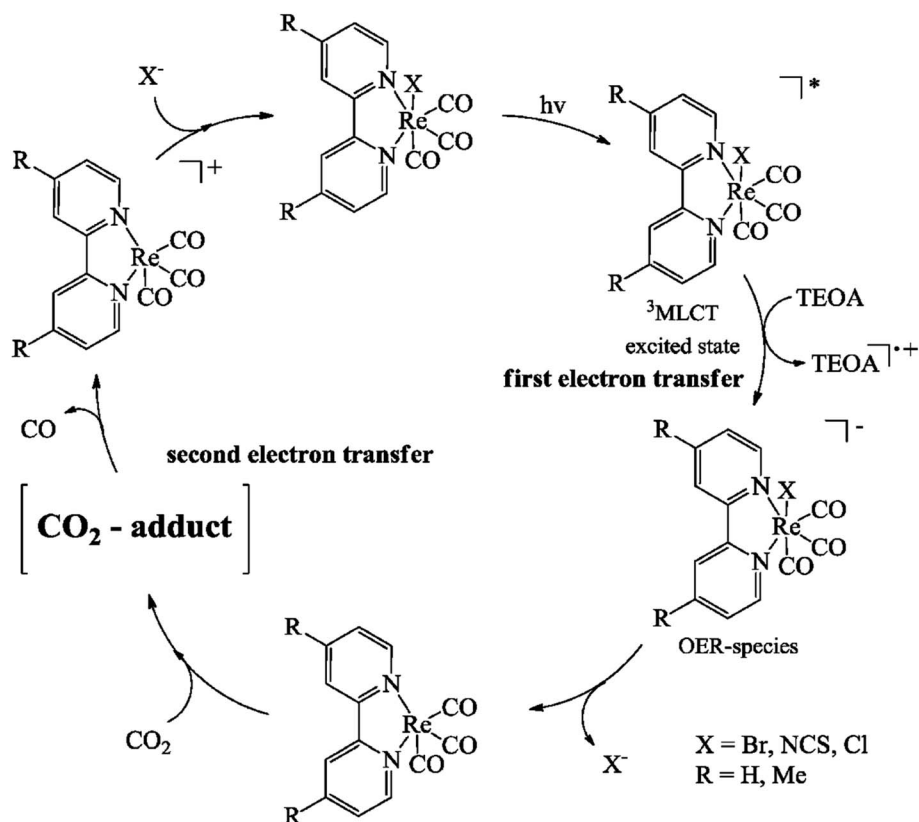


Fig. 10 Catalytic cycle for the photoreduction of CO<sub>2</sub> with (bipyridyl)Re(CO)<sub>3</sub>X complexes by Hawecker *et al.*<sup>68</sup>



TiO<sub>2</sub>, BaLa<sub>4</sub>TiO<sub>15</sub>, SrTiO<sub>3</sub>, WO<sub>3</sub>, NaNbO<sub>4</sub>, and Zn<sub>2</sub>GeO<sub>4</sub> are a few of the materials that show promise for use in these applications. Most of these inorganic semiconductors have good structural controllability and stability (the morphology, size, and surface). Titania-based materials, including 1-D (TiO<sub>2</sub> nanowires, nanorods, nanobelts, and nanotubes), 2-D (TiO<sub>2</sub> nanolayers and nanosheets), 3-D, and hierarchical nanostructures, are the most commonly employed catalysts.<sup>16</sup> Enhanced efficiency is attributed to factors such as high surface area, good photogenerated-charges separation, directional charge transport, enhanced light-harvesting owing to light trapping/scattering, and low photon influence, considering the configuration and geometry of the photocatalysts. Semiconductors such as ZnO, CdS, GaP, SiC, WO<sub>3</sub>, Ga<sub>2</sub>O<sub>3</sub>, GaP, InTaO<sub>4</sub>, MgO, ZrO<sub>2</sub>, BiVO<sub>4</sub>, and ATaO<sub>3</sub> are also used. Semiconductors with more negative CB potentials convert CO<sub>2</sub> to CH<sub>3</sub>OH. Water worked as a reductant since no reducing reagents were introduced into the reaction solutions.<sup>71,72</sup>

For example, it was reported that AgI/GCN nanocomposite's charge separation process follows the double-transfer mechanism (conventional charge separation mechanism) and Z-scheme process.<sup>73</sup> Upon irradiation, the AgI and GCN material's VB electrons are excited to CB. Therefore, the CO<sub>2</sub> photoconversion occurs at the surface of AgI if the double charge transfer mechanism is employed (Fig. 11a). However, when the Z-scheme mechanism is adopted, the photoconversion of CO<sub>2</sub> occurs on the surface of GCN because the CB value of GCN (−1.12 eV vs. NHE) is more negative than the standard reduction potential for the formation of O<sub>2</sub><sup>−</sup>, methane, ethanol and acetone, Fig. 11b.

**7.2.5.4. Hybrid nanocatalysts.** Hybrid materials are composites made by a synergistic combination of organic and inorganic components at the nanometer or molecular level. New properties are created by new electron orbitals formed between them. Hybrid materials such as a photocatalyst consisting of photosensitizer (CdSe quantum dots) and catalyst (Pt/TiO<sub>2</sub>) were reported.<sup>74</sup> CdSe quantum dots show a negative shift of CB energy where electron injection into titania can proceed under visible light in an aqueous media forming CH<sub>4</sub> and CH<sub>3</sub>OH. Nanoparticles supported on carbon nanotubes, g-C<sub>3</sub>N<sub>4</sub>,

graphene nanosheets, and carbon dots are used for CO<sub>2</sub> photoreduction under vis-light into CO.<sup>75–77</sup> The influence of dye-based organic linkers on CO<sub>2</sub> photoreduction efficiency has been reported using UiO-67. Re<sub>3</sub>-MOFs displayed high photocatalytic activity. When Ren-MOFs and Re<sub>3</sub>-MOFs were coated with silver nanoparticles, the efficiency was seven times enhanced, Fig. 12.<sup>78</sup>

Covalently bonded microporous organic polymers (MOPs) showed high physical and chemical stability. Cooper's group reported on several monomers synthesizing pyrene-based conjugated microporous polymers with 1.94–2.95 eV band gaps, exhibiting high photocatalytic activity.<sup>79</sup> Covalent triazine frameworks (CTFs) are a distinguished subclass of contemporary high-performance nanoporous materials. CTFs with aromatic triazine linkages are constructed by covalently linked light elements (C, N, and H) and boast high porosity, high nitrogen content, and good thermal/chemical stability. Furthermore, a triazine ring connected with electron-rich units can easily form p–n heterojunction *via* the conjugated structure, imparting superior nature to conjugated CTFs, particularly in terms of bandgap tunability and rapid electron separation rates.<sup>80,81</sup>

## 8. Pilot-scale projects and commercialization

Several well-known industries have expanded their funding for CCUS work. Also, various demonstration initiatives at the pilot scale are underway.<sup>82</sup> Examples are:

- CarbFix in Iceland for CO<sub>2</sub> capture from geothermal fluid and air.
- Drax in the UK for CO<sub>2</sub> capture from biomass power generation.
- STEPWISE in Sweden for sorption-enhanced water gas shift separation testing in the iron as well as the steel industry.
- CIUDEN in Spain for CO<sub>2</sub> storage.
- Geothermal plants for CCUS in Croatia for electricity generation from geothermal hot brine.

CCS is projected to play a key role in achieving global warming goals and turning CO<sub>2</sub> into useful goods.<sup>83,84</sup> As

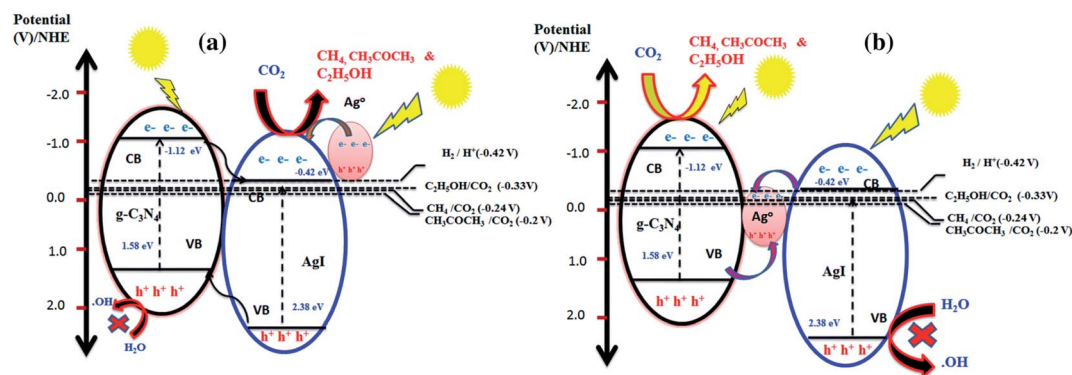


Fig. 11 Charge separation mechanism for photocatalytic conversion of CO<sub>2</sub> over AgI/GCN composite. (a) Double charge separation mechanism; (b) Z-scheme mechanism.<sup>73</sup>

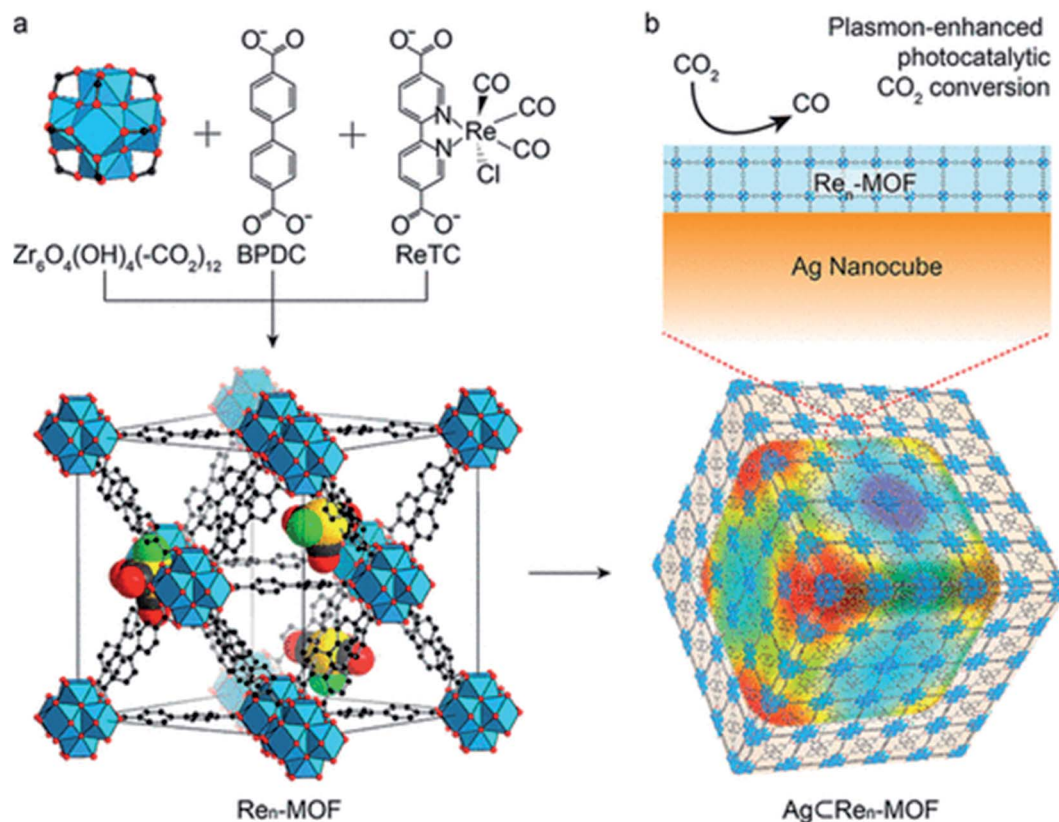


Fig. 12 Structures of Re<sub>n</sub>-MOF and Ag-Re<sub>n</sub>-MOF for plasmon-enhanced photocatalytic CO<sub>2</sub> conversion (a) and mechanism of conversion (b).<sup>78</sup>

a result, several technologies are being developed to capture, transport, store, and utilize CO<sub>2</sub>. Typically, technological development proceeds in stages: (i) bench or laboratory size, (ii) pilot scale, (iii) demonstration scale, and (iv) commercial scale.

These steps can be easily classified into numerous technology readiness levels (TRL), Fig. 13. At the TRL 3, TRL 6, and TRL 7 development stages, there is a glut of technology. Beyond TRL 3, improving a technology necessitates further research money, but methods beyond TRL 5 and TRL 7 necessitate major financial commitment and commercial interests, for example, in the case of some polymeric membranes. The following sections of this article go into greater detail about the technical development of the various CCS technologies.

## 9. CO<sub>2</sub> use market

Although it is difficult to assess the future market of CO<sub>2</sub> uses, there are some areas and applications of CO<sub>2</sub>. These can be listed as:

### 9.1. CO<sub>2</sub>-derived fuels

The carbon in CO<sub>2</sub> can be used to produce fuels that are in use today. The process involves using CO<sub>2</sub> in combination with hydrogen, which is highly energy-intensive to produce carbon-containing fuels that are easier to handle and use than pure hydrogen. Examples are methane, methanol, gasoline, and aviation fuels.

### 9.2. CO<sub>2</sub>-derived chemicals

The carbon and oxygen in CO<sub>2</sub> are promising to be used as an alternative to fossil fuels in producing chemicals, and materials including plastics, fibers, and synthetic rubber. Converting CO<sub>2</sub> to methanol and methane is the most technologically mature pathway.

### 9.3. CO<sub>2</sub> to building materials

CO<sub>2</sub> can be used to produce building materials to replace the water in concrete. It is called CO<sub>2</sub> curing or as a raw material in its constituents, cement, and construction aggregates. This process involves the reaction of CO<sub>2</sub> with calcium or magnesium to form low-energy carbonate molecules, the form of carbon that makes up concrete. While incorporating CO<sub>2</sub> in the manufacture of cement is still in its early stages of development, CO<sub>2</sub>-cured concrete is one of the most established and promising applications of CO<sub>2</sub> utilization.

Construction aggregates, tiny particles used in building materials, can be made by combining CO<sub>2</sub> with industrial or waste products from power plant activities. These include coal fly ash and iron slag, which would otherwise be heaped or kept in landfills, Fig. 14.

### 9.4. Crop yield boosting

CO<sub>2</sub> can be utilized to increase the yields of biological processes, such as algae growth and greenhouse crop



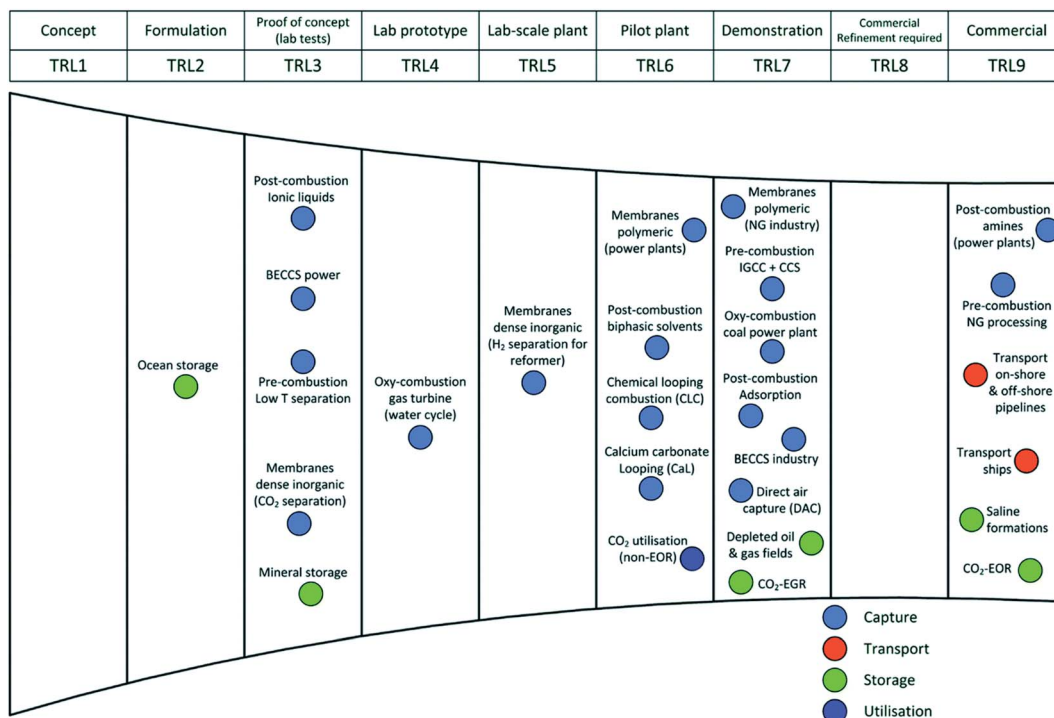


Fig. 13 Carbon collection, storage, and utilization technologies progressing in terms of technology readiness (TRL).<sup>85</sup>

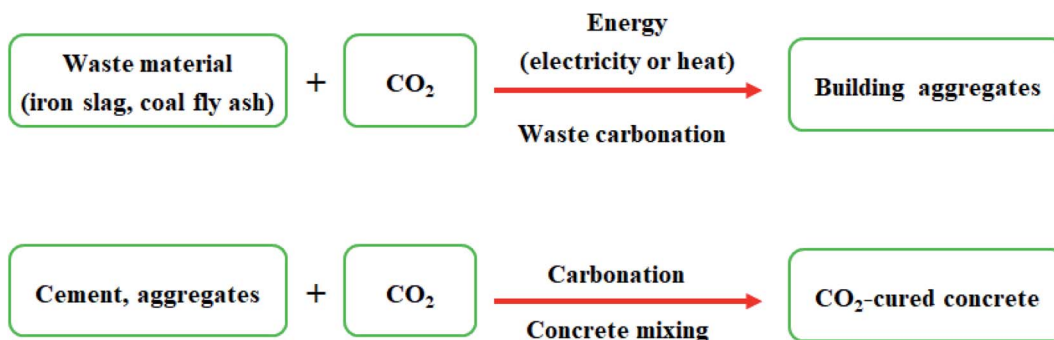


Fig. 14 CO<sub>2</sub> conversion pathways into CO<sub>2</sub>-derived building materials (building aggregates or CO<sub>2</sub>-cured concrete).

cultivation. The most developed use for increasing yields is using CO<sub>2</sub> with low-temperature heat in industrial greenhouses.

## 10. Conclusion and future perspective

In summary, one of the key issues facing our world is the rapid increase in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations. As a result, considerable interest has been in regulating CO<sub>2</sub> emissions and lowering atmospheric CO<sub>2</sub> concentrations to avoid a worldwide disaster. To reduce CO<sub>2</sub> emissions, various approaches have emerged including:

- Developing and converting to environmentally friendly energy sources;
- Improving energy efficiency and utilizing current processes;

- CO<sub>2</sub> collection and sequestration;
- Converting CO<sub>2</sub> to valuable products.

There has recently been a surge in interest in capturing CO<sub>2</sub> emissions and either permanently immobilizing them or chemically converting them into useful goods. This has prompted the creation of many strategies, approaches, and techniques aimed at reducing CO<sub>2</sub> levels through green energy alternatives as well as capturing and converting CO<sub>2</sub> into value-added products.

The use of CO<sub>2</sub> in commercial technology is based mostly on a trade-off between performance and environmental benefits.

Overall, this review is based on containing and utilizing CO<sub>2</sub> using organic-inorganic hybrid materials. The range of potential CO<sub>2</sub> uses involves direct use, by which CO<sub>2</sub> is not chemically altered (non-conversion), and the use of CO<sub>2</sub> by transformation, *via* multiple chemical and biological conversion processes to



fuels, chemicals, and building materials. The strategy/technologies come under CO<sub>2</sub>-Capture Utilization and Storage (CCUS). CCUS is far better than CCS because the former utilizes/transforms CO<sub>2</sub> into valuable products like ethylene, ethanol, methanol, formic acid, and formaldehyde. The transformations can be achieved using various materials, such as organic-inorganic hybrid-nanocomposites. Contemporary research should primarily focus on sustainable science to immediately address global warming.

The market for CO<sub>2</sub> use is expected to increase, with opportunities related to building materials, and as a carbon source for fuels and chemicals. However, some key factors affect the future market for CO<sub>2</sub>-derived products, including scalability, competitiveness and climate benefits, and the visibility of the technologies.

## Conflicts of interest

There are no conflicts to declare.

## References

- 1 IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva, Switzerland, 2014.
- 2 A. J. Nathanael, K. Kannaiyan, A. K. Kunhiraman, S. Ramakrishna and V. Kumaravel, Global opportunities and challenges on net-zero CO<sub>2</sub> emissions towards a sustainable future, *React. Chem. Eng.*, 2021, **6**, 2226–2247.
- 3 N. MacDowell, *et al.*, An overview of CO<sub>2</sub> capture technologies, *Energy Environ. Sci.*, 2010, **3**, 1645–1669.
- 4 S. VijayaVenkataRaman, S. Iniyar and R. Goic, A review of climate change, mitigation and adaptation, *Renewable Sustainable Energy Rev.*, 2012, **16**(1), 878–897.
- 5 N. P. Liyanage, W. Yang, S. Guertin, S. Sinha Roy, C. A. Carpenter, R. E. Adams, R. H. Schmehl, J. H. Delcamp and J. W. Jurss, Photochemical CO<sub>2</sub> Reduction with Mononuclear and Dinuclear Rhenium Catalysts Bearing a Pendant Anthracene Chromophore, *Chem. Commun.*, 2019, 55(7), 993–996.
- 6 K. O. Yoro, *Numerical Simulation of CO<sub>2</sub> Adsorption Behaviour of Polyaspartamide Adsorbent for PostCombustion CO<sub>2</sub> Capture*, MSc thesis, University of the Witwatersrand, Johannesburg, South Africa, 2017.
- 7 A. Gulzar, *et al.*, Carbon dioxide utilization: a paradigm shift with CO<sub>2</sub> economy, *Chem. Eng. J. Adv.*, 2020, **3**, 100013.
- 8 E. J. Granite and T. O'Brien, Review of novel methods for carbon dioxide separation from flue and fuel gases, *Fuel Process. Technol.*, 2005, **86**, 1423–1434.
- 9 H. Yang, Z. Xu, M. Fan, R. Gupta, R. B. Slimane, A. E. Bland and I. Wright, Progress in carbon dioxide separation and capture, *J. Environ. Sci.*, 2008, **20**, 14–27.
- 10 Z. Wang, Q. Ou, H. Ma, G. Cheng, Q.-P. Zhang, B. Tan and C. Zhang, Molecular Engineering for Organic Cage Frameworks with Fixed Pore Size to Tune Their Porous Properties and Improve CO<sub>2</sub> Capture, *ACS Appl. Polym. Mater.*, 2021, **3**(1), 171–177.
- 11 K. Pareek, Q. Zhang, R. Rohan and H. Cheng, Highly selective carbon dioxide adsorption on exposed magnesium metals in a cross-linked organo-magnesium complex, *J. Mater. Chem. A*, 2014, **2**, 13534–13540.
- 12 H. Ma, Z. Wang, Y.-H. Zhao, Q. Ou, B. Tan and C. Zhang, Microporous polymer based on hexaazatriphenylene-fused triptycene for CO<sub>2</sub> capture and conversion, *Sci. China Mater.*, 2020, **63**, 429–436.
- 13 J. T. Litynski, S. M. Klara, H. G. McIlvried and R. D. Srivastava, An overview of terrestrial sequestration of carbon dioxide: The United States Department of Energy's fossil energy R&D program, *Clim. Change*, 2006, **74**(1–3), 81–95.
- 14 M. Bonchio, M. Carraro, M. Gardan, G. Scorrano, E. Drioli and E. Fontananova, Hybrid photocatalytic membranes embedding decatungstate for heterogeneous photooxygenation, *Top. Catal.*, 2006, **40**, 133.
- 15 C. Oltra, P. Upham, H. Riesch, A. Boso, S. Brunsting, E. Dutschke and A. Lis, Public responses to CO<sub>2</sub> storage sites: lessons from five European cases, *Energy Environ.*, 2012, **23**, 227–248.
- 16 R. L. Newmark, S. J. Friedmann and S. A. Carroll, Water challenges for geologic carbon capture and sequestration, *Environ. Manage.*, 2010, **45**, 651–661.
- 17 T. Sakakura, J.-C. Choi and H. Yasuda, Transformation of carbon dioxide, *Chem. Rev.*, 2007, **107**, 2365–2387.
- 18 A. Pearson, Carbon dioxide—new uses for an old refrigerant, *Int. J. Refrig.*, 2005, **28**, 1140–1148.
- 19 W. Dale Spall and K. E. Laintz, *A Survey on the use of supercritical carbon dioxide as a cleaning solvent*, ed. M. John and P. S. Samuel, William Andrew Publishing, Westwood, NJ, 1998, pp. 162–194.
- 20 A. Baiker, Supercritical fluids in heterogeneous catalysis, *Chem. Rev.*, 1998, **99**, 453–474.
- 21 A. Laury and J. G. Sebranek, Use of carbon monoxide combined with carbon dioxide for modified atmosphere packaging of pre- and postrigor fresh pork sausage to improve shelf life, *J. Food Prot.*, 2007, **70**, 937–942.
- 22 N. Muradov, Industrial Utilization of CO<sub>2</sub>: a Win-Win Solution, in *Liberating Energy From Carbon: Introduction to Decarbonization*, Springer New York, New York, NY, 2014, pp. 325–383.
- 23 T. Inoue, A. Fujishima, S. Konishi and K. Honda, Photoelectrocatalytic reduction of carbon dioxide in aqueous suspensions of semiconductor powders, *Nature*, 1979, **277**, 637.
- 24 E. Alper and O. Orhan, CO<sub>2</sub> utilization: developments in conversion processes, *Petroleum*, 2017, **3**(1), 109–126.
- 25 A. N. Mistry, U. Ganta, J. Chakrabarty and S. Dutta, A review on biological systems for CO<sub>2</sub> sequestration: organisms and their pathways, *Environ. Prog. Sustainable Energy*, 2019, **38**, 127–136.
- 26 A. Nisar, S. Khan, M. Hameed, A. Nisar, H. Ahmad and S. Azhar Mehmood, Bio-conversion of CO<sub>2</sub> into biofuels



- and other value-added chemicals via metabolic engineering, *Microbiol. Res.*, 2021, **251**, 126813.
- 27 B. Cornils and W. A. Hermann, *Applied Homogeneous Catalysis with Organometallic Compounds*, VCH, Weinheim, 1996, vol. 2, p. 1048.
  - 28 J. Ma, N. Sun, X. Zhang, N. Zhao, F. Xiao, W. Wei and Y. Sun, A short review of catalysis for CO<sub>2</sub> conversion, *Catal. Today*, 2009, **148**(3–4), 221–231.
  - 29 M. D. Porosoff, B. Yan and J. G. Chen, Catalytic reduction of CO<sub>2</sub> by H<sub>2</sub> for synthesis of CO, methanol and hydrocarbons: challenges and opportunities, *Energy Environ. Sci.*, 2016, **9**, 62–73.
  - 30 A. Ramirez, L. Gevers, A. Bavykina, S. Ould-Chikh and J. Gascon, Metal organic framework-derived Iron catalysts for the direct hydrogenation of CO<sub>2</sub> to short chain olefins, *ACS Catal.*, 2018, **8**, 9174–9182.
  - 31 R. Francke, B. Schille and M. Roemelt, Homogeneously Catalyzed Electroreduction of Carbon Dioxide—Methods, Mechanisms, and Catalysts, *Chem. Rev.*, 2018, **118**, 4631–4701.
  - 32 G. K. Ramesha, J. F. Brennecke and P. V. Kamat, Origin of Catalytic Effect in the Reduction of CO<sub>2</sub> at Nanostructured TiO<sub>2</sub> Films, *ACS Catal.*, 2014, **4**(9), 3249–3254.
  - 33 G. Liu, W. Jin and N. Xu, Graphene-based membranes, *Chem. Soc. Rev.*, 2015, **44**, 5016–5030.
  - 34 J. H. Lee, H. J. Lee and J. W. Choi, Unveiling anomalous CO<sub>2</sub>-to-N<sub>2</sub> selectivity of graphene oxide, *Phys. Chem. Chem. Phys.*, 2017, **19**, 22743–22748.
  - 35 J. Y. Tang, X. Y. Kong, B. J. Ng, *et al*) Midgap-state-mediated two-step photoexcitation in nitrogen defect-modified g-C<sub>3</sub>N<sub>4</sub> atomic layers for superior photocatalytic CO<sub>2</sub> reduction, *Catal. Sci. Technol.*, 2019, **9**, 2335–2343.
  - 36 G. Qi, L. Fu and E. P. Giannelis, Sponges with covalently tethered amines for high-efficiency carbon capture, *Nat. Commun.*, 2014, **5**, 5796.
  - 37 T. Endo, D. Nagai, T. Monma, H. Yamaguchi and B. Ochiai, A Novel Construction of a Reversible Fixation–Release System of Carbon Dioxide by Amidines and Their Polymers, *Macromolecules*, 2004, **37**, 2007–2009.
  - 38 S. Supasitmongkol and P. Styring, High CO<sub>2</sub> solubility in ionic liquids and a tetraalkylammonium-based poly(ionic liquid), *Energy Environ. Sci.*, 2010, **3**, 1961–1972.
  - 39 D. Wu, F. Xu, B. Sun, R. Fu, H. He and K. Matyjaszewski, Design and Preparation of Porous Polymers, *Chem. Rev.*, 2012, **112**, 3959–4015.
  - 40 P. Bhanja, A. Modak and A. Bhaumik, Porous Organic Polymers for CO<sub>2</sub> Storage and Conversion Reactions, *ChemCatChem*, 2019, **11**, 244–257.
  - 41 P. Kaur, J. T. Hupp and S. T. Nguyen, Porous Organic Polymers in Catalysis: Opportunities and Challenges, *ACS Catal.*, 2011, **1**, 819–835.
  - 42 S. Cao, F. Tao, Y. Tang, Y. Li and J. Yu, Size- and shape-dependent catalytic performances of oxidation and reduction reactions on nanocatalysts, *Chem. Soc. Rev.*, 2016, **45**, 4747–4765.
  - 43 Y. Tamaki and O. Ishitani, Supramolecular Photocatalysts for the Reduction of CO<sub>2</sub>, *ACS Catal.*, 2017, **7**(5), 3394–3409.
  - 44 D. Raciti and C. Wang, Recent Advances in CO<sub>2</sub> Reduction Electrocatalysis on Copper, *ACS Energy Lett.*, 2018, **3**, 1545–1556.
  - 45 R. Shi, G. I. N. Waterhouse and T. Zhang, Recent Progress in Photocatalytic CO<sub>2</sub> Reduction Over Perovskite Oxides, *Sol. RRL*, 2017, **1**, 1700126.
  - 46 J. Hou, S. Cao, Y. Wu, Z. Gao, F. Liang, Y. Sun, Z. Lin and L. Sun, Inorganic Colloidal Perovskite Quantum Dots for Robust Solar CO<sub>2</sub> Reduction, *Chem.–Eur. J.*, 2017, **23**, 9481–9485.
  - 47 M. S. Denny Jr, J. C. Moreton, L. Benz and S. M. Cohen, *Nat. Rev. Mater.*, 2016, **1**, 16078, Metal–organic frameworks for membrane-based separations.
  - 48 X. Y. Chen, V.-T. Hoang, D. Rodrigue and S. Kaliaguine, Postsynthetic Methods for the Functionalization of Metal–Organic Frameworks, *RSC Adv.*, 2013, **3**, 24266–24279.
  - 49 A. Razzaq and S. Il In, TiO<sub>2</sub> Based Nanostructures for Photocatalytic CO<sub>2</sub> Conversion to Valuable Chemicals, *Micromachines*, 2019, **10**, 326.
  - 50 M. Rebber, C. Willa and D. Koziej, Organic–inorganic hybrids for CO<sub>2</sub> sensing, separation and conversion, *Nanoscale Horiz.*, 2020, **5**, 431–453.
  - 51 A. S. Varela, W. Ju and P. Strasser, Molecular Nitrogen–Carbon Catalysts, Solid Metal Organic Framework Catalysts, and Solid Metal/Nitrogen-Doped Carbon (MNC) Catalysts for the Electrochemical CO<sub>2</sub> Reduction, *Adv. Energy Mater.*, 2018, **8**, 1703614.
  - 52 S. Zhang, Q. Fan, R. Xia and T. J. Meyer, CO<sub>2</sub> Reduction: From Homogeneous to Heterogeneous Electrocatalysis, *Acc. Chem. Res.*, 2020, **53**(1), 255–264.
  - 53 S. A. Rawool, K. K. Yadav and V. Polshettiwar, Defective TiO<sub>2</sub> for photocatalytic CO<sub>2</sub> conversion to fuels and chemicals, *Chem. Sci.*, 2021, **12**, 4267.
  - 54 X. Chang, T. Wang and J. Gong, CO<sub>2</sub> photo-reduction: insights into CO<sub>2</sub> activation and reaction on surfaces of photocatalysts, *Energy Environ. Sci.*, 2016, **9**, 2177–2196.
  - 55 C.-C. Wang, Y.-Q. Zhang, J. Li and P. Wang, Photocatalytic CO<sub>2</sub> reduction in metal–organic frameworks: a mini review, *J. Mol. Struct.*, 2015, **1083**, 127–136.
  - 56 W.-N. Wang, J. Souliis, Y. J. Yang and P. Biswas, Comparison of CO<sub>2</sub> photoreduction systems: a review, *Aerosol Air Qual. Res.*, 2014, **14**, 533–549.
  - 57 X. Li, J. Yu, S. Wageh, A. A. Al-Ghamdi and J. Xie, Graphene in photocatalysis: a review, *Small*, 2016, **48**, 6640–6696.
  - 58 L. Liu and Y. Li, Understanding the reaction mechanism of photocatalytic reduction of CO<sub>2</sub> with H<sub>2</sub>O on TiO<sub>2</sub>-based photocatalysts: a review, *Aerosol Air Qual. Res.*, 2014, **14**, 453–469.
  - 59 S. N. Habisreutinger, L. Schmidt-Mende and J. K. Stolarczyk, Photocatalytic reduction of CO<sub>2</sub> on TiO<sub>2</sub> and other semiconductors, *Angew. Chem., Int. Ed.*, 2013, **52**, 7372–7408.
  - 60 M. Marszewski, S. Cao, J. Yu and M. Jaroniec, Semiconductor-based photocatalytic CO<sub>2</sub> conversion, *Mater. Horiz.*, 2015, **2**, 261–278.
  - 61 X. Xiang, F. Pan and Y. Li, A review on adsorption-enhanced photoreduction of carbon dioxide by nanocomposite materials, *Adv. Compos. Hybrid Mater.*, 2018, **1**, 6–31.



- 62 L.-L. Tan, W.-J. Ong, S.-P. Chai and A. R. Mohamed, Photocatalytic reduction of CO<sub>2</sub> with H<sub>2</sub>O over graphene oxide-supported oxygen-rich TiO<sub>2</sub> hybrid photocatalyst under visible light irradiation: Process and kinetic studies, *Chem. Eng. J.*, 2017, **308**, 248–255.
- 63 J. C. Wu, H.-M. Lin and C.-L. Lai, Photo reduction of CO<sub>2</sub> to methanol using optical-fiber photoreactor, *Appl. Catal., A*, 2005, **296**, 194–200.
- 64 S. Delavari and N. A. S. Amin, Photocatalytic conversion of CO<sub>2</sub> and CH<sub>4</sub> over immobilized titania nanoparticles coated on mesh: Optimization and kinetic study, *Appl. Energy*, 2016, **162**, 1171–1185.
- 65 A. Khalilzadeh and A. Shariati, Photoreduction of CO<sub>2</sub> over heterogeneous modified TiO<sub>2</sub> nanoparticles under visible light irradiation: Synthesis, process and kinetic study, *Sol. Energy*, 2018, **164**, 251–261.
- 66 R. Reithmeier, C. Bruckmeier and B. Rieger, Conversion of CO<sub>2</sub> via Visible Light Promoted Homogeneous Redox Catalysis, *Catalysts*, 2012, **2**(4), 544–571.
- 67 H. Takeda and O. Ishitani, Development of efficient photocatalytic systems for CO<sub>2</sub> reduction using mononuclear and multinuclear metal complexes based on mechanistic studies, *Coord. Chem. Rev.*, 2010, **254**, 346–354.
- 68 J. Hawecker, J.-M. Lehn and R. Ziessel, Photochemical and Electrochemical Reduction of Carbon Dioxide to Carbon Monoxide Mediated by (2,2'-Bipyridine) tricarbonylchlororhenium(I) and Related Complexes as Homogeneous Catalysts, *Helv. Chim. Acta*, 1986, **69**, 1990–2012.
- 69 H. S. Whang, J. Lim, M. S. Choi, *et al.*, Heterogeneous catalysts for catalytic CO<sub>2</sub> conversion into value-added chemicals, *BMC Chem.*, 2019, **1**, 9.
- 70 H. Miura, K. Endo, R. Ogawa and T. Shishido, Supported palladium-gold alloy catalysts for efficient and selective hydrosilylation under mild conditions with isolated single palladium atoms in alloy nanoparticles as the main active site, *ACS Catal.*, 2017, **7**(3), 1543–1553.
- 71 H. Pan and D. Michael, Heagy, Photons to Formate: A Review on Photocatalytic Reduction of CO<sub>2</sub> to Formic Acid, *Nanomaterials*, 2020, **10**, 2422.
- 72 S. R. Lingampalli, M. M. Ayyub and C. N. R. Rao, Recent Progress in the Photocatalytic Reduction of Carbon Dioxide, *ACS Omega*, 2017, **2**(6), 2740–2748.
- 73 P. Murugesan, S. Narayanan and M. Matheswaran, Visible light photocatalytic conversion of CO<sub>2</sub> in aqueous solution using 2D-structured carbon-based catalyst-coated  $\beta$ , $\gamma$ -AgI nanocomposite, *J. Mater. Sci.*, 2019, **54**, 7798–7810.
- 74 C. Wang, R. L. Thompson, J. Baltrus and C. Matranga, Visible Light Photoreduction of CO<sub>2</sub> Using CdSe/Pt/TiO<sub>2</sub> Heterostructured Catalysts, *J. Phys. Chem. Lett.*, 2010, **1**, 48–53.
- 75 M. Li, L. Zhang, X. Fan, Y. Zhou, M. Wu and J. Shi, Highly selective CO<sub>2</sub> photoreduction to CO over g-C<sub>3</sub>N<sub>4</sub>/Bi<sub>2</sub>WO<sub>6</sub> composites under visible light, *J. Mater. Chem. A*, 2015, **3**, 5189–5196.
- 76 J. Yu, J. Jin, B. Cheng and M. Jaroniec, A noble metal-free reduced graphene oxide–CdS nanorod composite for the enhanced visible-light photocatalytic reduction of CO<sub>2</sub> to solar fuel, *J. Mater. Chem. A*, 2014, **2**, 3407–3416.
- 77 Y.-F. Xu, M.-Z. Yang, B.-X. Chen, X.-D. Wang, H.-Y. Chen, D.-B. Kuang and C.-Y. Su, A CsPbBr<sub>3</sub> Perovskite Quantum Dot/Graphene Oxide Composite for Photocatalytic CO<sub>2</sub> Reduction, *J. Am. Chem. Soc.*, 2017, **139**(16), 5660–5663.
- 78 K. M. Choi, D. Kim, B. Rungtaweeworanit, C. A. Trickett, J. T. D. Barmanbek, A. S. Alshammari, P. Yang and O. M. Yaghi, Plasmon-enhanced photocatalytic CO<sub>2</sub> conversion within metal–organic frameworks under visible light, *J. Am. Chem. Soc.*, 2017, **139**(1), 356–362.
- 79 R. S. Sprick, J.-X. Jiang, B. Bonillo, S. Ren, T. Ratvijitvech, P. Guiglion, M. A. Zwijsburg, D. J. Adams and A. I. Cooper, Tunable Organic Photocatalysts for Visible-Light-Driven Hydrogen Evolution, *J. Am. Chem. Soc.*, 2015, **137**(9), 3265–3270.
- 80 T. Zhao, Q. Niu, G. Huang, Q. Chen, Y. Gao, J. Bi and L. Wu, Rational construction of Ni(OH)<sub>2</sub> nanoparticles on covalent triazine-based framework for artificial CO<sub>2</sub> reduction, *J. Colloid Interface Sci.*, 2021, **602**, 23–31.
- 81 C. Zhu, Q. Fang, R. Liu, D. Wen, S. Song and Y. Shen, Insights into the Crucial Role of Electron and Spin Structures in Heteroatom-Doped Covalent Triazine Frameworks for Removing Organic Micropollutants, *Environ. Sci. Technol.*, 2022, **56**(10), 6699–6709.
- 82 A. J. Nathanael, K. Kannaiyan, A. K. Kunhiraman, S. Ramakrishna and V. Kumaravel, Global opportunities and challenges on net-zero CO<sub>2</sub> emissions towards a sustainable future, *React. Chem. Eng.*, 2021, **6**, 2226–2247.
- 83 *IPCC Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
- 84 A. Cousins, L. Wardhaugh and A. Cottrell, *Pilot plant operation for liquid absorption-based post-combustion CO<sub>2</sub> capture*, *Absorption-based Post-combustion Capture of Carbon Dioxide*, Woodhead Publishing, Cambridge, UK, 2016, pp. 649–684.
- 85 M. Bui, *et al.*, Carbon capture and storage (CCS): the way forward, *Energy Environ. Sci.*, 2018, **11**, 1062–1176.

