

## REVIEW



# A critical review of current conversion facilities and research output on carbon dioxide utilization

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## ABSTRACT

- 1. A literature survey using Cochran's model on the global CO<sub>2</sub> utilization facilities based on location and product type and the recent publications on CO<sub>2</sub> conversion to value-added products is presented.*
- 2. Most existing CO<sub>2</sub> conversion facilities produce chemical intermediates, polymers, urea, and building materials, while most of the research output focused on CO<sub>2</sub> conversion to chemical intermediates, polymers, building materials, and fuels*
- 3. A future perspective on the need to increase CO<sub>2</sub> conversion facilities and research output on fuel synthesis to aid the aviation and maritime sectors' decarbonization was also highlighted.*

Carbon capture and storage (CCS) has struggled over the past few decades to demonstrate the economic viability of CO<sub>2</sub> sequestration. Consequently, this study reviewed the existing integrated carbon capture utilization facilities and the published articles on CO<sub>2</sub> conversion to building materials, chemical intermediates, fuels, urea, and polymers. Representative sample sizes were determined, and the analysis of the current CO<sub>2</sub> conversion facilities and volume of published articles between 2016 and 2022 were done based on a 90% confidence limit within a 9.93% margin of error and a 95% confidence limit within a 5% margin of error, respectively. The results showed that over 90% of global CO<sub>2</sub> conversion facilities produce chemical intermediates, urea, polymers, and building materials, and less than 10% produce fuels. More than half of the global CO<sub>2</sub> conversion facilities are in South-East Asia (mainly China), with the remaining in Western Europe (23%), North America (20%), and Oceania (3%). The analysis of the research publications within the time under investigation showed that the research focus is currently on CO<sub>2</sub> conversion to chemical intermediates, polymers, building materials, and fuels (over 95%) and less on urea.

**Keywords** carbon dioxide · circular economy · environment · reuse · sustainability

## Discussion

The economic viability of the CCS technology has been on the front burner of every aspect of energy (primarily from fossils) sustainability in recent times. Some experts have stated that more focus should be placed on achieving net-zero emissions than the energy transition. They argue that even the mining and processing of the “finite” metals used for manufacturing the so-called “clean” tech equipment, just like their fossil counterparts, also result in the emission of greenhouse gases. Consequently, producing carbon-neutral fuels is a more realistic pathway for tackling climate change and attaining environmental sustainability. The conversion of CO<sub>2</sub> to chemical intermediates, polymers, building materials, and fuels has been identified as a viable way of creating a business case for the CCUS process. However, there is currently no consensus on which products will most likely provide a positive balance sheet for the CCUS process.

## Introduction

The atmospheric concentration of poisonous gases, due to human activities, has been rising extensively since the Industrial Revolution. It has reached dangerous levels not seen in the last 3 million years and has continually increased. Without significant control and conversion to valuable products, it will become a major disaster for the ecosystem. CO<sub>2</sub>, which accounts for over 70% of all greenhouse gases, is prominent among these poisonous gases. According to the IEA 2021,<sup>1</sup> global CO<sub>2</sub> emissions declined by 5.8% in 2020. CO<sub>2</sub> emissions were lower than energy demand in 2020 due to the pandemic hitting interest for other fossil-derived fuels, especially oil and coal, while renewables increased. Despite the decrease in 2020, global energy-related CO<sub>2</sub> emissions remained at 31.5 Gt, which added to CO<sub>2</sub> reaching its highest-ever average annual concentration in the atmosphere of 412.5 parts per million in 2020, around half higher than when the industrial revolution began. In 2021 worldwide, energy-related CO<sub>2</sub> emissions were projected to bounce back and increase by 4.8% as coal, oil, and gas demand returned with the economy. The increment of more than 1500 Mt CO<sub>2</sub> would be the most significant increase since the carbon-intensive economic recovery from the worldwide financial crisis over ten years. It leaves worldwide emissions in 2021 of around 1.2% (about 400 Mt), below the 2019 peak. However, carbon dioxide is now a recognized carbon feedstock for the chemical supply chain, becoming an alternative to oil and gas.

Key industries required for industrialization, like cement, petrochemicals, oil and gas, power, steel, chemicals, and other heavy-emitting industries, are responsible for a large proportion of CO<sub>2</sub> emissions globally. As the world strives to meet the net-zero emission target in the coming decades, balancing sustainability becomes highly imperative for societies to thrive. Sustainability is most likely to be achieved by capturing and utilizing the stored CO<sub>2</sub> as fuel, electricity, chemical feedstocks, and other value-added products. One proven and established technology by which CO<sub>2</sub> is captured is carbon capture utilization and storage (CCUS). CCUS has the potential to sequester about 90% of harmful CO<sub>2</sub> emissions from heavy-emitting-related industries<sup>2</sup> and help create a sustainable environment. It will, therefore, be crucial and is expected to play a critical role in the clean energy transition agenda. The main types of CCUS are pre-combustion, post-combustion, and oxy-fuel technologies. Detailed descriptions and processes of CCUS technologies can be found elsewhere.<sup>3,4</sup>

The utilization of the captured CO<sub>2</sub> provides an economic justification for the carbon capture and storage (CCS) process. The utilization of CO<sub>2</sub> is basically through direct (non-conversion) and indirect (conversion) methods. Various review publications on CO<sub>2</sub> utilization have analyzed the multiple techniques of CO<sub>2</sub> utilization (simulations, biochemical, catalytic, and electrochemical) to obtain numerous value-added products. While some studies centered on a few products,<sup>5-7</sup> others analyzed only a single product.<sup>8-15</sup> Published studies on a wide variety of CO<sub>2</sub>-derived products where up to six (6) and more products are analyzed and compared simultaneously are scarce in the open

literature. This broad coverage is significant for selecting the best possible technique(s), process conditions, and products at a glance.

In general, there are three methods by which CO<sub>2</sub> can be converted into chemical products. They include.

- The application of physical energy such as electricity.
- Choosing suitable oxidized low-energy synthetic targets such as organic carbonates.
- Using high-energy materials such as hydrogen.

Forecasting and identifying market opportunities in CO<sub>2</sub> utilization technology in terms of viability, readiness, markets, and momentum is highly imperative. According to the CO<sub>2</sub>U<sup>16</sup> research report, there have been tremendous advancements in CO<sub>2</sub> utilization recently, and many methods have proven to be scalable. Accordingly, four critical markets have been identified as viable priorities for CO<sub>2</sub> utilization. They are building materials, chemical intermediates, fuels, and polymers. The CO<sub>2</sub>U<sup>16</sup> report also identifies eight product categories within the four critical markets that should be pursued based on their technological maturity, commercial potential, and potential impact on carbon emission reduction. These product categories are:

### (a) Building materials

- Concrete
- Carbonate aggregates

### (b) Chemical intermediates

- Methanol
- Formic acid
- Syngas

### (c) Fuels

- Liquid fuels and
- Methane

### (d) Polymers

- Polyols
- Polycarbonates

The majority of the conversion process in the open literature is by hydrogenation, chemical, electrochemical, photocatalytic, and thermal conversion. Consequently, this study will focus on CO<sub>2</sub> conversion literature via hydrogenation, chemical, electrochemical, photocatalytic, and thermal conversion. The primary reason for this study is the massive amount of literature being churned out on the subject without proper synthesis of the available knowledge. For instance, a good way of measuring CO<sub>2</sub> emission mitigation compliance globally can be in terms of

existing CCUS facilities. Also, the percentage share of the total number of research publications on the value creation of CO<sub>2</sub> conversion will provide valuable insight into the various products derivable from CO<sub>2</sub> conversion. Hence, there is a need to summarize findings so researchers, operators, and other stakeholders can understand the best prospects. Understanding the best means of converting CO<sub>2</sub> to value-added products relative to other sources of producing the same products will help shape the direction of the CO<sub>2</sub> utilization research area. Also, the knowledge of the global distribution of CO<sub>2</sub> utilization facilities will help identify the regions/countries at the forefront of CO<sub>2</sub> capture and utilization and those lagging behind. This approach helps measure regions' and countries' commitments and compliance in mitigating CO<sub>2</sub> emissions. These are essential gaps in knowledge that need to be explored. The basis of the research publication literature analysis will be articles published on CO<sub>2</sub> utilization between 2016 and 2022.

## Research methodology

This study is a systematic review of published articles or data on existing CO<sub>2</sub> utilization facilities and published research articles on CO<sub>2</sub> utilization (from 2016 to 2022). The research papers, including peer-reviewed journal publications, books, study reports, newsletters, and conference proceedings, were sourced from the Google search engine. After removing duplicates and screening, 69 CO<sub>2</sub> conversion facilities and 425 research publications on CO<sub>2</sub> utilization, obtained from over 500 published articles, were used for the study. The Cochran model<sup>17</sup> was adopted to determine the representative sample sizes for the study. Table 1 shows the values of the statistical parameters used in determining the representative sample size by Cochran's model.

From the sample size analysis, it can be seen that a minimum sample size of 69 is needed to analyze the data on CO<sub>2</sub> utilization facilities, with a confidence limit of 90%, a population proportion of 0.5, and a margin of error of 9.93%. At the same time, a minimum number of 385 research articles is required to investigate the data on published research on CO<sub>2</sub> utilization, with a confidence limit of 95%, a standard deviation of 0.5, and a margin of error of 5%. The margin of error for the CO<sub>2</sub> conversion facilities was raised to 9.93% while reducing the confidence limit to 90% due to the scarcity of the required data. A confidence

limit of 90% and above and a margin of error of less than 10% is considered adequate in obtaining representative samples for data analysis. For the published articles on CO<sub>2</sub> conversion to value-added products, this study will focus on the products identified in the CO<sub>2</sub>U<sup>16</sup> report as viable materials. In addition, research publications on the conversion of CO<sub>2</sub> to DME and urea will be included in this study to broaden the scope of products that are derivable from CO<sub>2</sub>.

Furthermore, these products were selected because of their premium significance in sustainable industrialization, economic development, and energy security of any society. The outputs of each product of CO<sub>2</sub> utilization are presented in two sections. The first section analyses the various existing facilities for CO<sub>2</sub> conversion, while the second section analyses the various research publications on CO<sub>2</sub> utilization. The method of production and output generated is also stated. The key process parameters at which the optimum values are achieved are also reported for better specificity of the results.

## Analysis of CO<sub>2</sub> conversion facilities and published articles

This section highlights and synthesizes published data on existing CO<sub>2</sub> conversion facilities as well as published articles on CO<sub>2</sub> conversion to value-added products selected in line with the objectives of this study between 2016 and 2022. The analyses are presented as follows:

### CO<sub>2</sub> conversion facilities

Different facilities are used to obtain various value-added products using CO<sub>2</sub> as feed. Some facilities convert CO<sub>2</sub> to single products like methanol, DME, Urea, polymer, formic acid (FA), syngas, fuels, and building materials; others convert CO<sub>2</sub> to more than one product. The main aim of this section is to present and analyze data on the existing conversion facilities to determine their location, quantity, and the specific product they are designed to produce. The conversion facilities are presented as follows.

### CO<sub>2</sub>-methanol facilities

Methanol is a common feedstock for several synthetic chemicals. The main value-added products obtained from methanol

**Table 1.** Statistical parameters for sample size determination.

Parameters	Confidence limit (%)	Population proportion	Margin of error (%)	Minimum sample size
CO <sub>2</sub> conversion facilities	90	0.5	9.93	69
Research articles	95	0.5	5.00	385

include formaldehyde, acetic acid, methyl tertiary-butyl ether, and dimethyl ether.<sup>18</sup> Its transformation into olefins is an emerging sector. Figure 1 shows a block diagram of methanol production from CO<sub>2</sub> hydrogenation.

Tables 2 and 3 show the existing and planned methanol industrial and commercial facilities worldwide. It is worthy of note that the planned methanol facilities in Table 3 were not used in the data analysis but rather to highlight the anticipated growth of CO<sub>2</sub> to methanol conversion facilities in the near future.

#### CO<sub>2</sub>-DME facilities

Dimethyl ether (DME) is a natural compound primarily utilized as airborne fuel and as a reagent for creating broadly applied mixtures such as dimethyl sulfate and acetic acid.<sup>33</sup> Dimethyl ether is a new and reasonable synthetic fuel that can substitute liquefied petroleum gas (LPG) or mixed in fuel mixture to its excellent combustion properties (cetane number = 55–60). DME has the potential to be fed into diesel engines, which would be only slightly modified, and its combustion prevents soot formation.<sup>34</sup> The one-step and two-step Dimethyl ether production processes are relatively well established. Figure 2 shows the schematic of the production process of DME from CO<sub>2</sub> hydrogenation, while Table 4 shows the existing DME industrial and commercial facilities worldwide.

#### CO<sub>2</sub>-polymer facilities

About 400 million tonnes of polymers are created worldwide annually. The amount has been developing by 3–4% each year for quite a long time, and they have become a vital and significant piece of the advanced world. Regardless of their valuable and adaptable material properties, polymers face a significant issue: 90% of them are produced from fossil carbon and end up as CO<sub>2</sub> emissions.<sup>39</sup>

Generally, the plastics industry cannot be decarbonized because carbon is the primary atom in their material structures. In this context, renewable alternatives to fossil feedstocks are required. Chemicals and polymers produced today now utilize renewable carbon, mostly from biomass. However, as biomass and the recycling of plastics alone will not suffice in bridging the gap in demand for polymers and plastics, carbon-dioxide utilization could be the solution to polymer production in the future.<sup>40</sup>

One such way of producing polymers from CO<sub>2</sub> is hydrogenation. Figure 3 shows the schematic of the polymer production process from CO<sub>2</sub> hydrogenation, while Table 5 shows the existing industrial and commercial facilities worldwide.

#### CO<sub>2</sub>-urea facilities

Due to its significance in fertilizer production, urea is industrially produced on an immense scale. In 2019, for instance, annual world production was around 218 million tonnes. Urea is constantly synthesized from ammonia and carbon dioxide. Large quantities of CO<sub>2</sub> are often generated during ammonia production, beginning from nitrogen available in the air and hydrogen produced from natural gas. As a result, urea production facilities are almost always located adjacent to the site where ammonia is produced.<sup>47</sup> Aside from the CO<sub>2</sub> generated during ammonia production, captured CO<sub>2</sub> from other carbon-intensive processes can also be used with hydrogen to make urea. Figure 4 shows the schematic of the urea production process from CO<sub>2</sub> hydrogenation, while Table 6 shows the existing CO<sub>2</sub> to urea industrial and commercial facilities worldwide.

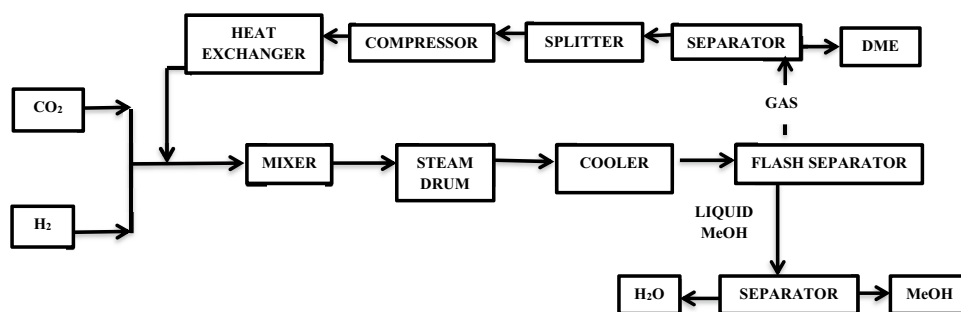
#### CO<sub>2</sub>-FA facilities

Within the limits of our literature search, there is no carbon dioxide conversion facility to FA, probably because methanol can serve as a feedstock for producing FA. FA is used as a chemical intermediate in adhesives, preservatives, dimethylformamide (DMF), and other products.<sup>16</sup> Figure 5 shows the schematic of the process of producing FA from carbon-dioxide hydrogenation.

#### CO<sub>2</sub>-building materials facilities

One proven way to lower emissions from the building and construction industry is the conversion of CO<sub>2</sub> into concrete and other building material aggregates. It is one of the most mature and efficient CCU technology. Businesses are effectively transforming CO<sub>2</sub> into building materials thanks to research and innovation. Project activities that capture waste CO<sub>2</sub> that would have otherwise been released into the atmosphere can utilize the gas as a feedstock in concrete construction. By creating a type of concrete that sequesters CO<sub>2</sub> into the material itself, which has an added benefit, and by

**Figure 1.** Methanol production process via CO<sub>2</sub> hydrogenation.



**Table 2.** Existing facilities for CO<sub>2</sub> to methanol production.

Country	Company	Start-up year	Methanol production (t/year)	CO <sub>2</sub> tonnes recycling per year	Source
Germany	TOTAL/Sunfire e-CO <sub>2</sub> Met project	2020	70,000	–	[18]
Germany	Hydrogen Engineering/Institute for Renewable Energy Systems (IRES)	2020	10	–	[18]
Japan	Mitsui and Celanese Corporation	2009	130,000	180,000	[18]
Korea	Korean Institute of Science and Technology (KIST) /CAMERE process	2004	37	–	[18]
China	Dalian Institute of Chemical Physics	2020	1000	–	[18]
Denmark	Power2Met Danish Consortium	2019	287	–	[18]
Iceland	CRI	2011	4000	5500	[19]
Germany	MEFCO <sub>2</sub>	2019	500	–	[20]
Sweden	FReSMe	2019	365	–	[21]
Germany	Carbon2Chem	2020	18	–	[22]
Canada	Bioindustrial Industrial Canada	2020	1,800,000	426,022	[23]
Qatar	Qatar Fuel Additives Company (QAFAC)	2014	982,350	182,500	[24]
China	Shunli	2022	110,000	500,000	[25]
Belgium	Consortium of 7 at the port of Antwerp	2022	8000	–	[26]
Switzerland	Swiss Liquid Future	2012	75L/d	6000	[27]

developing concrete that uses less Portland cement, these project activities aim to minimize greenhouse gas emissions. The sequestering of CO<sub>2</sub> lowers emissions by taking gas that would have otherwise been emitted and capturing, compressing, and transporting it to a site where it can be embedded into the concrete. Lowering the cement required in the concrete further reduces emissions because cement production is a high-energy and carbon-intensive process.<sup>58</sup> Figure 6 shows the schematic of converting CO<sub>2</sub> to calcium carbonate for

cement and concrete production. Table 7 shows the existing facilities for concrete production.

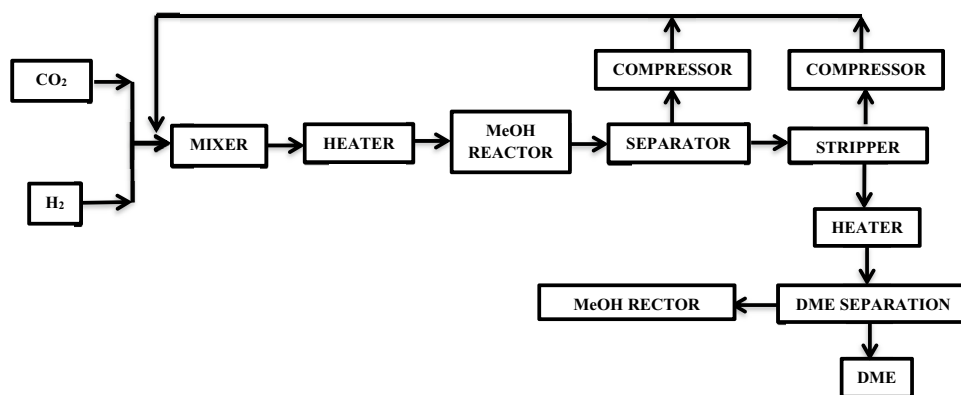
#### CO<sub>2</sub>-syngas and fuels

The conversion of CO<sub>2</sub> to syngas and fuels offers an alternative pathway to waste utilization and decarbonization. Conventional syngas are produced from fossil-based sources like natural gas and coal via various chemical processes, including

**Table 3.** Planned facilities for CO<sub>2</sub> to methanol production.

Country	Company	Start-up year	Methanol production (t/years)	CO <sub>2</sub> tonnes recycling per year	Source
Australia (Tasmania)	ABEL	2023	60,000–70000	–	[18]
Sweden	Liquid Wind	2023 (plan for six facilities by 2030)	45,000	90,000	[28]
Norway	A Consortium of Companies/ CRI	2024	100,000	146,000	[29]
Belgium	A Consortium of 10 at the port of Ghent	–	44,000	140,000	[30]
Germany	Dow	–	200,000	330,000	[31]
Denmark	A Consortium of companies	2024	100,000	146,000	[32]

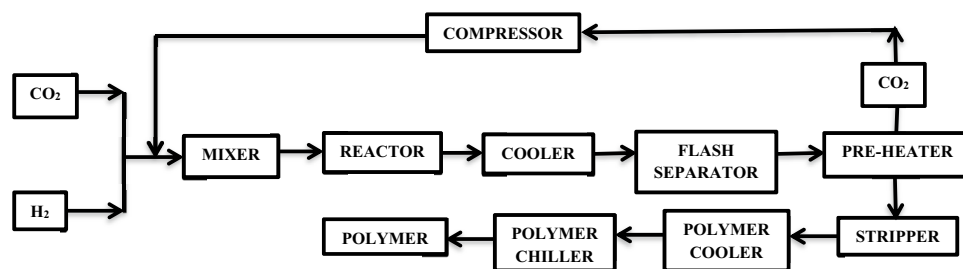
**Figure 2.** DME production process via CO<sub>2</sub> hydrogenation.



**Table 4.** Existing facilities for DME production.

Country	Company	Start-up year	DME production (t/years)	CO <sub>2</sub> tonnes recycling per year	Source
South Korea	KOGAS	2008	1,095,000	–	[35]
Germany	ALIGN-CCUS Project DME from CO <sub>2</sub>	2020	183	–	[36]
United States	Oberon Fuel	2013	16,425	–	[37]
China	BASF and Lutianhua	2020	110,000	–	[38]

**Figure 3.** Polymer production process via CO<sub>2</sub> hydrogenation.



the electrochemical reduction of the produced CO<sub>2</sub>. However, sustainable and clean syngas can also be made from CO<sub>2</sub> gasification of multiple materials, using specific catalysts to obtain the desired products. Carbon-neutral fuels like jet fuels, more efficient gasoline, and liquid hydrocarbons can be produced from CO<sub>2</sub> conversion via several chemical processes. The conversion of CO<sub>2</sub> to these fuels, including syngas, can enhance energy security while helping to achieve the net-zero emission targets. Despite the numerous benefits, only a few commercial conversion facilities are available globally (see Tables 8 and 9).

### Published articles on CO<sub>2</sub> conversion

This section contains the data on the published literature on the conversion of carbon dioxide to different value-added products, including methanol, urea, DME, FA, polymer, building materials, syngas, and fuels. There are various methods by which CO<sub>2</sub> can be converted into other products. These methods are photochemical, biochemical, electrochemical, thermal, and chemical. The pros and cons of the different techniques of CO<sub>2</sub> conversion into other products can be found elsewhere.<sup>9</sup> Published literature from 2016 to 2022 on the conversion of CO<sub>2</sub> to the selected products chosen for this study is analyzed and presented in the following sections. This literature analysis was done to synthesize the available knowledge on CO<sub>2</sub> conversion studies to clearly determine the significant areas of focus for researchers on the subject matter in recent times.

#### CO<sub>2</sub>-methanol

Catalytic hydrogenation of a mixture of CO<sub>2</sub> is the basis of syngas processes. These syngas processes make it possible to produce a variety of chemical products, including methanol. A careful survey of published works revealed two main research approaches for CO<sub>2</sub> to methanol conversion. They are theoretical (simulation) and experimentation. Table 10 shows the carbon dioxide conversion to methanol analysis via different methods.

#### CO<sub>2</sub>-dimethyl ether

Despite numerous studies on DME production, there is still a lack of process simulations for directly converting carbon dioxide to DME. Its distinguishing feature at the most conceptual level is that DME is synthesized directly from synthesis gas and is called a “direct” or “one-step” process. By contrast, the conventional process is called the “indirect” or “two-step” process

because DME is produced from an intermediate product, methanol. Table 11 shows the results of the literature analysis on CO<sub>2</sub> to DME for the period under investigation.

Compared to the indirect method, the direct method of converting CO<sub>2</sub> to DME is more cost-effective, with a higher return on investment and CO<sub>2</sub> utilization impact.<sup>145,146,152</sup>

#### CO<sub>2</sub>-polymer

Different CO<sub>2</sub>-based monomers and polymers like polyester, polyureas, polyurethanes, polyols, and polycarbonates are produced from CO<sub>2</sub> and have been commercialized. Still, it remains to be seen if the technology can compete. Reduction in the cost of CO<sub>2</sub> and/or greater incentives to reduce carbon emissions must be implemented for CO<sub>2</sub> utilization to polymers to compete with conventional feedstock.<sup>169</sup> The data on the published work on CO<sub>2</sub> to polymer is presented in Table 12.

#### CO<sub>2</sub>-FA

Currently, FA is used as a chemical intermediate in adhesives, preservatives, DMF, and other products. Because it's more reactive than methanol, FA is more suitable as a chemical intermediate. Research in the reduction of carbon dioxide to FA (CH<sub>2</sub>OH) is still early-stage. FA also has been proposed as a fuel source for fuel cells. This application is still in the proof-of-concept phase.<sup>273</sup> Converting harmful CO<sub>2</sub> to beneficial FA is a step in the right direction. Consequently, several researchers have been working on CO<sub>2</sub> conversion to FA. Some of the results are presented in Table 13.

#### CO<sub>2</sub>-urea

The production of urea uses large amounts of CO<sub>2</sub>, which can be obtained from any CO<sub>2</sub>-generating process, including carbon sequestration. A few researchers have published works on CO<sub>2</sub> to urea conversion. Table 14 shows the literature analysis of the published works within the period under investigation.

#### CO<sub>2</sub>-building materials

The conversion of CO<sub>2</sub> to concrete and other building aggregates is one of the primary sectors identified by the CO<sub>2</sub> utilization roadmap's concentration of active developers.<sup>328</sup> Solid carbonates are created from converting gaseous CO<sub>2</sub> from industrial point sources or ambient air, and they can either supplement or replace concrete components. The three leading CO<sub>2</sub> utilization

**Table 5.** Existing facilities for CO<sub>2</sub> to polymer production.

Country	Company	Start-up year	Polymer production (t/years)	Final products	Source
China	Taizhou Bangfeng Plastic Co., Ltd	–	30,000	Polypropylene carbonate	[39]
China	Jiangsu Nantong Xingchen Synthetic Material Co., Ltd	–	60,000	Polypropylene carbonate	[39]
China	Shanghai Bangkai Plastics Technology Co., Ltd	–	30,000	Polypropylene carbonate	[39]
Germany	Covestro	2016	60,000	Polycarbonates polyols for polyurethane	[41]
U.S.	Empower materials	2015	500	Poly(ethylene carbonate), poly(propylene carbonate), poly(propylene/cyclohexene carbonate), and poly(cyclohexene carbonate)	[41]
Japan	Asahi Kasei Plastics (Changshu) Co., Ltd	2020	750,000	Aromatic polycarbonates	[42]
China	Jiangsu Zhongke Jinlong-cas Chemical Co	2003	10,000	Polypropylene carbonate polyol	[43]
China	Jilin Boda New Materials Co. Ltd	–	50,000	Polyethylene carbonate, polypropylene carbonate, etc.	[44]
China	Inner Mongolia Shuangxin Environment-Friendly Material Co., Ltd-	–	3,000	Poly(ethylene carbonate), poly(propylene carbonate), and poly(propylene/cyclohexene carbonate)	[45]
Taiwan	Asahi Kasei	2002	50,000	Polycarbonate	[46]
Saudi Arabia	Asahi Kasei	2011	260,000	Polycarbonate	[46]
South Korea	Asahi Kasei	2012	80,000	Polycarbonate	[46]



Table 5. (continued)

Country	Company	Start-up year	Polymer production (t/years)	Final products	Source
Saudi Arabia	SABIC and ExxonMobil	2016	400,000	Halobutyl rubber, Polybuta-diene, and styrene-butadiene rubber, ethylene propylene-diene monomer (EPDM) rubbers, thermoplastic elastomers (TPE), carbon black	[46]
Japan	Phosgene	1995	40,000	Polycarbonate	[46]
Singapore	Phosgene	1999	60,000	Polycarbonate	[46]
China	Phosgene	2012	80,000	Polycarbonate	[46]

technologies used in the building materials industry for the production of concrete via CO<sub>2</sub> mineralization include<sup>58</sup>;

- CO<sub>2</sub> curing: CO<sub>2</sub> replaces energy-intensive steam curing to decrease cement content and boost strength while mineralizing and storing carbon in precast and ready-mix concrete.
- Carbonation: A solid carbonate is created when CO<sub>2</sub> interacts with Ca or MgO. This substance supplements or replaces traditional concrete components (e.g., aggregates, SCMs).
- CO<sub>2</sub>-based-cements: In making cement, CO<sub>2</sub> is used as a raw material, replacing traditional Portland cement.

Since the nineteenth century, Portland cement has been the industry standard. Limestone, a primary raw material for Portland cement, emits carbon dioxide when burned in a cement kiln. More than 55% of emissions associated with cement production are attributable to this process. Portland cement can be replaced with other cements that emit significantly fewer greenhouse gases for any application.<sup>328</sup> Table 15 shows the published works on CO<sub>2</sub> to building materials within the period under investigation.

#### CO<sub>2</sub>-syngas and fuel

Syngas, a vital fuel, is critical for synthesizing many chemicals, including hydrogen, and the various chemicals and fuels considered in this study. It consists primarily of H<sub>2</sub> and CO. Syngas differs chemically from other gases produced by gasification processes typically carried out at low temperatures because it uses higher pressures to synthesize chemicals and fuels.<sup>272</sup> Global syngas production accounts for about 2% of primary energy use. However, the syngas market, primarily from fossil fuels, is dominated by the ammonia industry globally.<sup>402,403</sup> Jet fuels, methane, gasoline, and liquid hydrocarbon fuels are other fuels that can be produced from CO<sub>2</sub> conversion via several chemical processes. Tables 16 and 17 show published literature on syngas and fuel synthesis.

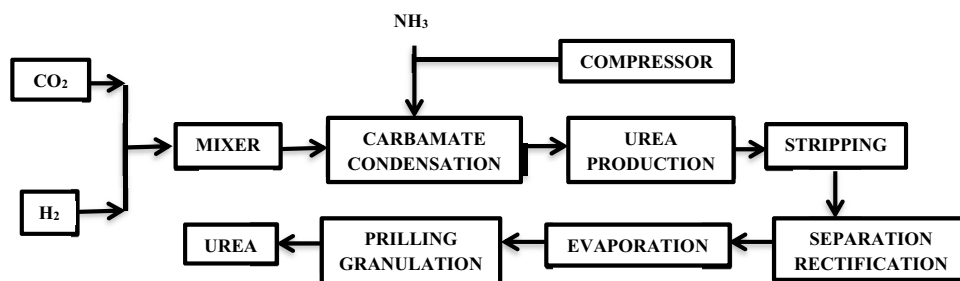
## Results and discussion

This section provides an analysis of the results. The data on CO<sub>2</sub> utilization were compared in two ways. The first was to obtain vital information on the various existing conversion facilities, and the second was to provide information on the products of core interests to researchers through published articles.

#### Analysis of the existing carbon dioxide utilization facilities

Based on the sampled data, the distribution of the CO<sub>2</sub> conversion facilities globally showed that while some continents are leading in the CO<sub>2</sub> conversion processes to mitigate greenhouse gas emissions, others are still lagging. From the results of the

**Figure 4.** Urea production process via CO<sub>2</sub> hydrogenation.



analysis in Fig. 7, most conversion facilities are located in Asia (mainly in China), followed by Europe (Western Europe), and then North America (Mainly in the US). The high number of CO<sub>2</sub> conversion facilities in Asia, driven mainly by China and India, can be attributed to the commitment of both countries (and other countries in the region) to minimize emissions from their rapid industrialization drive in recent times. China, the second-largest economy globally, has been on a steady path of rapid industrialization. This rapid industrialization growth rate comes with massive emissions of GHGs, especially CO<sub>2</sub>. Hence, China has become one of the industrialized hubs with the highest emission index. Likewise, the stringent net-zero emissions targets and environmental sustainability regulations and policies may be responsible for the relatively significant share of carbon capture facilities in Europe and North America. Most of the facilities in Asia convert CO<sub>2</sub> to polymer, urea, and chemical intermediates. In Europe, the facilities mainly produce chemical intermediates from CO<sub>2</sub>. Building materials feedstocks are the predominant products obtained from CO<sub>2</sub> conversion in North America. The facility distribution and CO<sub>2</sub> conversion options in the regions are mainly driven by stringent regulatory policies occasioned by the need to decarbonize and mitigate greenhouse gas emissions for environmental sustainability, meeting net-zero emission targets, providing an economic justification for CCS projects, and the increasing demand for raw materials, chemicals, and fuels, which are in high demand in any industrialized societies.

The relatively insignificant or absence of CO<sub>2</sub> conversion facilities in many developing countries in Africa, South America, Eastern Europe, other developing Asian countries, and the Middle East (excluding Saudi Arabia) show the weakness or lack of clear policy and stringent greenhouse gas emission mitigation regulations. It can also be attributed to the reluctance of many countries in these regions to meet net-zero emission targets since they contribute the least emissions globally. Most of these developing countries depend primarily on fossil fuels for energy, and their lack of decarbonization strategies could undermine global efforts to combat climate change due to greenhouse emissions.

Figure 8 shows the percentage distribution of the global carbon dioxide utilization facilities based on value-added products. The results show that there are more facilities converting CO<sub>2</sub> to chemical intermediate products like methanol, DME, and syngas (29%), urea (25%), and polymers (23%) than there are for

building materials (16%) and fuels (7%). The data suggests that over 90% of the global CO<sub>2</sub> conversion facilities produce chemical intermediates, urea, polymers, and building materials. The development of CCUS facilities is driven primarily by the need to decarbonize and create a sustainable environment. Minimizing the high carbon footprints associated with the conventional processes from which these materials are produced could be responsible for the relatively high amount of CO<sub>2</sub> conversion facilities. As the global population rises, more people will require more energy for sustainability. More energy will most likely result in industrialization, which requires certain feedstocks as building blocks. Hence, the demand for these feedstocks is expected to rise. The rising demand for these feedstocks and the need for environmental sustainability (in this case, carbon neutrality) explains why the majority of CO<sub>2</sub> conversion facilities produce chemical intermediates (methanol, DME, Syngas, FA) as well as urea, polymers, and building materials.

The inadequate or lack of facilities for FA (an important chemical intermediate) production from CO<sub>2</sub> could be due to several technical and economic reasons. Its demand remains low, and unless more specific beneficial applications are developed, its utilization might remain challenging.<sup>169</sup> Overall, CO<sub>2</sub> conversion to raw materials, chemicals, and fuels is mainly governed by economics, especially when there are alternative feedstocks for producing the same chemicals and fuels. The economics and availability of alternative materials may be responsible for the relatively low number of CO<sub>2</sub> conversion facilities to fuels globally. Therefore, the number of CO<sub>2</sub> conversion facilities to raw materials, chemicals, and fuels will only increase when it becomes cost-effective and sustainable to use CO<sub>2</sub> as feedstock for the conversion processes.

### Analysis of published articles on CO<sub>2</sub> conversion

Figure 9 compares the volume of published research on the conversion of CO<sub>2</sub> to various products under investigation. Based on the sampled data, the results showed that the published articles in the last 6 years were more on chemical intermediates (45%), polymers (24%), and building materials (17%) than there were for fuels (11%) and urea (3%). The relatively high number of published articles on chemical intermediates (methanol, DME, FA, and Syngas) and polymers could result from their high demand and usefulness as a feedstock in many chemical and industrial processes. The statistical results from

**Table 6.** Existing facilities for CO<sub>2</sub> to Urea production.

Country	Company	Start-up year	Urea production (t/y)	CO <sub>2</sub> tonnes recycling per day	Final products	Source
China	BASF and Lutianhua	2020	1,580,000	–	Ammonia and urea	[39]
Russia	PJSC Metafrax/Casale SA	2021	629,625	1200	Ammonia, urea and melamine	[48]
India	National Fertilizers Limited (Vijaipur)	2012	478,150	450	NH <sub>3</sub> and urea	[48]
Pakistan	Engro Fertilizers Limited	2011	1,300,000	340	NH <sub>3</sub> and urea	[48]
Vietnam	Petrovietnam Fertilizer and Chemicals Corporation	2010	2,190,000	240	NH <sub>3</sub> and urea	[48]
Oman	Sohar International Urea and Chemical Industries Co	2009	1,277,500	–	NH <sub>3</sub> and urea	[48]
India	Nagarjuna Fertilizers and Chemicals Limited (Kakinada)	2006	1,500,000	450	NH <sub>3</sub> and urea	[48]
United Arab Emirates	Ruwais Fertilizer Industries	2009	2,117,000	400	NH <sub>3</sub> and urea	[49]
Bahrain	National Oil and Gas Holding Company (NOGA Holding)	1998	620,500	450	NH <sub>3</sub> and urea	[50]
Kuwait	petrochemical industries co. (bsc)	1985	1700	1700	NH <sub>3</sub> and urea	[50]
India	Indian Farmers Fertiliser Co-operative Ltd. (Aonla)	2009	2,000,000	450	NH <sub>3</sub> and urea	[51]
India	Indian Farmers Fertiliser Co-operative Ltd. (phulpur)	2006	1,416,000	450	NH <sub>3</sub> and urea	[52]
Malaysia	Petronas Fertilizer (Kedah) Sdn Bhd	1999	1,405,250	200	NH <sub>3</sub> and urea	[53]
Indonesia	P.T. Pupuk Kalimantan Timur	2002	3,430,000	–	NH <sub>3</sub> and urea	[54]

Table 6. (continued)

Country	Company	Start-up year	Urea production (t/y)	CO <sub>2</sub> tonnes recycling per day	Final products	Source
New Zealand	Kapuni Ammonia-Urea Facility	1983	265,000	–	NH <sub>3</sub> and urea	[55]
Australia	Perdaman chemical and fertilizer pty Ltd		2,300,000		NH <sub>3</sub> and urea	[56]
China	KAPSOM/Henan Xin-lianxin Chemicals	2011	200,000		Urea, formaldehyde resin, and melamine	[57]

Figure 5. Formic-acid production process (electrochemical reduction) via CO<sub>2</sub> hydrogenation.

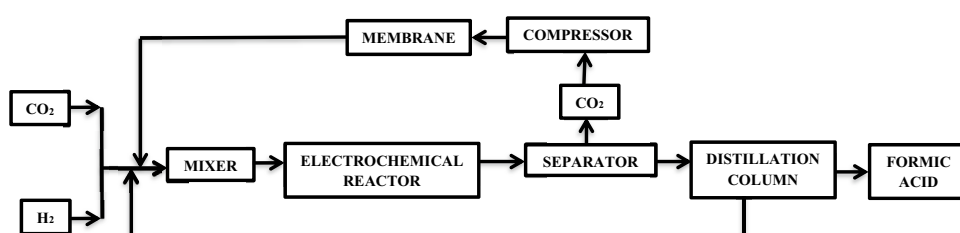
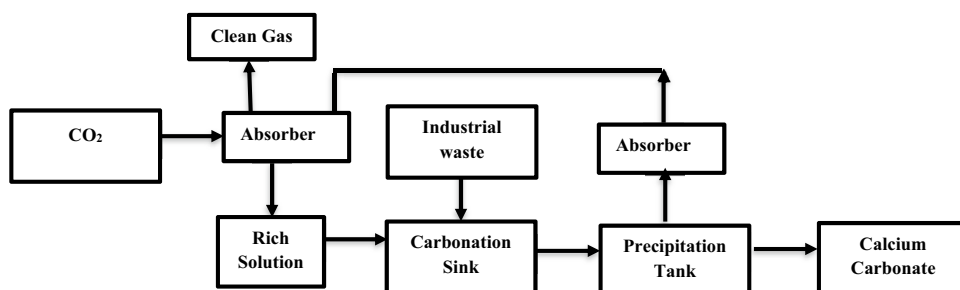


Figure 6. Typical schematic of a calcium carbonate facility via CO<sub>2</sub> and industrial waste.



the analysis of published articles in this study align with that of existing conversion facilities except for urea. The high number of published articles on chemical intermediates, followed by polymers and building materials, can be attributed to the fact that since most of the existing conversion facilities produce these materials, researchers focus more on improving and optimizing their production processes from the existing facilities. In addition, the high volume of published articles could be due to the increased market demand for these products and the urgent need to decarbonize the industrial sector. Furthermore, the special attention on chemical intermediates, polymers, and building materials may be that they provide the outlets for making CCUS economically viable.<sup>16</sup> Although there are also many other efforts to convert other greenhouse gases, like methane CH<sub>4</sub>, to some chemical intermediates like methanol,<sup>485,486</sup> chemicals,<sup>487-489</sup> and solar fuels,<sup>490</sup> most research interests tilt towards CO<sub>2</sub> conversion rather than CH<sub>4</sub>, most likely because CO<sub>2</sub> accounts for a more significant percentage of greenhouse gasses (76%) than

methane (16%).<sup>491</sup> Hence, the general focus, like this study, is more on CO<sub>2</sub> conversion. The attention of researchers on the transformation of CO<sub>2</sub> to building materials (17%), especially concrete in the building materials industry, stems from the need to decarbonize the concrete (a critical raw material required for industrialization) production industry, which is energy-intensive with a high carbon footprint.

The absence or inadequacy of direct or indirect CO<sub>2</sub> to FA facilities could be responsible for the relatively higher volume of research on the area. The relatively low volumes of research on urea (3%) could be because the technologies for converting CO<sub>2</sub> to these products are pretty well established, and there are other efficient and cost-effective feedstocks for their production. As a result, there is little novelty in using CO<sub>2</sub> as a feedstock, resulting in little work to optimize the grey areas. In addition, the conventional urea production process is an energy- and carbon-intensive technology that contradicts the idea of carbon neutrality. Furthermore, since urea was not listed as one

**Table 7.** Existing facilities for building materials production.

Country	Company	CO <sub>2</sub> used (t/y)	CO <sub>2</sub> recycled	Products	Source
Canada	CarbiCrete's technology	20,000	Nil	Carbonated blocks	[58]
Canada	CarbonCure Technologies,	–	Nil	Concrete	[59]
United States (Greenfield)	Irving Materials, Inc.,	–	Yes	Concrete	[60]
United States (Los Angeles)	Carbon Upcycling UCLA	–	Nil	Concrete	[61]
United States	Ozinga	–	yes	Concrete	[62]
United States	Thomas Concrete's	–	Yes	Concrete	[63]
Japan	Kajima Corporation	–	Nil	CO <sub>2</sub> -SUICOM	[64]
United States	Solidia	–	Nil	Cement and concrete	[64]
United Kingdom	O.C.O Technology	225,000	Nil	Aggregates and fills for blocks, concrete, and screed	[64]
United States	Blue planet	–	Yes	Aggregates	[64]
United States	Calera	30,000	Nil	Carbonate precipitates	[64]

of the priorities for CO<sub>2</sub> utilization<sup>16</sup> and hence might not be a viable economic route for the CCUS process, researchers may be unwilling to conduct studies on CO<sub>2</sub> conversion to urea, explaining why there is a low volume of publications in this area in recent times. Nonetheless, continuous efforts should be made to develop novel, cost-effective, and sustainable technologies for converting CO<sub>2</sub> to these and many other products. This is a sure way of making the decarbonization process attractive, cost-effective, and competitive.

**Table 8.** Existing facilities for syngas production.

Country	Company	CO <sub>2</sub> used (kg/h)	CO <sub>2</sub> temp. (°C) and pressure (bar)	Syngas (Nm <sup>3</sup> /h)	Source
Germany	SUNFIRE-SYNLINK SOEC	730	0–40 6–8	750	[65]

### Analysis of processes and catalysts used for CO<sub>2</sub> conversion

CO<sub>2</sub> transformation into various value-added products can be classified under the following major processes: Photochemical, Electrochemical, Thermal, and Chemical.<sup>9,492–495</sup> The characteristics of these processes are shown in Table 18. The catalysts used in these various processes to obtain a desired product are further highlighted.

#### Catalyst for CO<sub>2</sub> conversion to methanol

The methods of converting carbon dioxide into methanol are affected by two significant factors. They include reaction conditions and catalyst properties.<sup>496</sup> The various categories of catalysts used for the production of methanol include<sup>496</sup>,

- Cu-based catalyst
- Precious metal-base catalyst
- Other catalysts

**Cu-based catalyst** Cu-based catalyst is the most used catalyst for methanol production via Carbon dioxide<sup>496</sup>; however, in order to achieve total activity, they require

**Table 9.** Existing facilities for fuel production.

Country	Company	Startup year	CO <sub>2</sub> used (kg/h)	Product	Source
China	BASF and Lutianhua	2020	–	100,000 MTPA of Diesel exhaust fluid (DEF)	[39]
US	Twelve	–	1E+6	E-Jet	[66]
UK	LanzaTech UK Ltd.	2023	–	79 KTA of E-Jet	[67]
Canada	Carbon Engineering	2020	–	200 barrels of synthetic fuel	[68]
Italy	Climeworks	–	150	Jet Fuel	[69]

pre-treatment in hydrogen, which is inconvenient for small-scale onboard systems. This method relies on heterogeneous Cu–ZnO catalysts, where Cu is the active phase, and ZnO is a crucial promoter to increase the system's activity. Commercial Cu/ZnO/Al<sub>2</sub>O<sub>3</sub> catalyst development has advanced noticeably in recent years despite numerous disputes on the reaction mechanism.<sup>497–500</sup> With the application of Cu–ZnO catalysts, high deactivation and low activities are observed. This has led to significant efforts in developing catalysts to improve the high deactivation of Cu–ZnO catalysts and the low activity.<sup>501</sup> Another disadvantage is that Cu/ZnO catalysts have a heightened sensitivity to a few parts per million of sulfur and have the potential to exhibit pyrophoric activity when exposed to air.<sup>502</sup> This type of catalyst has good activity, high methanol selectivity, low operating pressure, and temperature, so it is an excellent choice for hydrogenation catalysts in carbon dioxide conversion to methanol.<sup>503</sup>

**Precious metal-based catalyst** Precious metal-based catalysts (Au, Pd, Pt, Ga, Rh) have drawn a lot of interest in converting carbon dioxide to methanol due to their high activity in adsorption and dissociation of hydrogen. Some metal-based catalysts, such as Palladium (Pd), as the active metal, exhibit high results for methanol production. However, to produce methanol using pure Pd, they are usually combined with other metals as promoters. In this case, the methanol selectivity is affected by the type of promoters used.<sup>496</sup> This type of catalyst will generate a high methanol selectivity at a very high temperature.<sup>496</sup>

**Other catalyst** High temperatures act as an equilibrium restriction on the hydrogenation of carbon dioxide to methanol. A catalyst often functions most effectively above room temperature, necessitating extraordinary thermal

stability. Therefore, the thermal stability criterion must be closely followed if catalysts other than Cu and precious metal-based catalysts are to be utilized.<sup>496</sup>

#### Catalyst for CO<sub>2</sub> conversion to DME

Compared to photocatalytic or electrocatalytic methods, carbon dioxide's one-step heterogeneous catalytic conversion to value-added compounds shows better efficiency. Nevertheless, in practical demonstrations and applications, conventional catalysts for the one-step carbon dioxide hydrogenation to DME still have inadequate space–time yield and stability. From this angle, the recent progress in the one-step carbon dioxide hydrogenation to DME is concentrated on various catalytic systems through an analysis of published experimental findings and the reaction mechanism, which includes the catalytic properties of carbon dioxide molecules, activation modes and active sites under specific conditions.<sup>504</sup> The various categories of catalysts used for the production of DME include<sup>496</sup>;

- Cu-based catalyst
- Precious metal-base catalyst
- Oxide-derived bifunctional catalyst

**Cu-based catalyst** Cu-based catalysts are the most thoroughly researched catalysts in early studies. The well-known bifunctional catalyst (CZA) coupling with acidic sites is first used in carbon dioxide hydrogenation to DME.<sup>504</sup> Cu-based catalysts have not yet found practical usage in the carbon dioxide hydrogenation of DME. Nevertheless, there is still room for improvement in the catalytic performance, including DME selectivity, catalytic activity, and stability. To achieve this, investigating the nature of active sites and the reaction mechanism becomes necessary.<sup>504</sup>

**Table 10.** Studies on CO<sub>2</sub> conversion to methanol.

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	270/45	Chemical (experiment)	Cu/ZnO-based	–	2020	[8]
CO <sub>2</sub> /H <sub>2</sub>	–	Review	Cu/ZnO-based	–	2019	[10]
CO <sub>2</sub> /H <sub>2</sub>	180/30	Chemical (Experimental)	CZCZ <sub>3</sub>	–	2019	[11]
CO <sub>2</sub> /H <sub>2</sub>	25/1	Chemical (Simulation – CHEMCAD)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	> 99.9	2016	[70]
CO <sub>2</sub> /H <sub>2</sub>	503/76.98	Chemical (Simulation)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2017	[71]
CO <sub>2</sub> /H <sub>2</sub>	232/50	Chemical (Simulation – Unisim/COSMOL)	Cu-based	–	2018	[72]
CO <sub>2</sub> /H <sub>2</sub>	300/1	Chemical (Aspen Plus V8.8 Simulation)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	99.5	2022	[72]
CO <sub>2</sub> /H <sub>2</sub>	40/20	Chemical (Simulation – Hysys V10.1)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	99.5	2020	[73]
CO <sub>2</sub> /H <sub>2</sub>	183.6/57.8	Chemical (Simulation – Hysys V8.8)	–	99.5	2019	[74]
CO <sub>2</sub> /H <sub>2</sub>	220/50	Chemical (Simulation – Aspen Plus)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2019	[75]
CO <sub>2</sub> /H <sub>2</sub>	80/30	Chemical (Simulation – economics)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	99	2017	[76]
CO/CO <sub>2</sub> /H <sub>2</sub>	260/30	Chemical (Experimental)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2017	[77]
CO <sub>2</sub> /H <sub>2</sub>	250/50	Chemical (Experimental)	Cu and Fe-based	99.9	2017	[78]
CO <sub>2</sub> /H <sub>2</sub>	25/1	Chemical (Simulation)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	99.9	2019	[79]
CO <sub>2</sub> /H <sub>2</sub>	300/25	Chemical (Simulation – Hysys V10)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2020	[80]
CO <sub>2</sub> /H <sub>2</sub>	/ 50	Chemical (Simulation – Aspen Plus)	–	–	2019	[81]
CO <sub>2</sub> /NG/Steam	550/5	Chemical (Simulation – Plus)	Cu based	–	2016	[82]

**Table 10.** (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	240/5	Chemical (Experiment – isotope labeling experiments)	Au/ZnO	–	2016	[83]
CO <sub>2</sub> /H <sub>2</sub>	250/22.5	Chemical (Experiment – Impregnation Technique)	Cu/ZnO-SBA-15	92	2017	[84]
CO/CO <sub>2</sub> /H <sub>2</sub>	210/78	Chemical (Simulation – Aspen Plus)	–	98.7	2018	[85]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (Valorization)	–	–	2016	[86]
CO <sub>2</sub> /H <sub>2</sub>	250/20	Chemical (Experimental)	Pd/ZnO	99	2016	[87]
CO <sub>2</sub> /H <sub>2</sub>	250/20	Chemical (Experimental)	C <sub>1</sub> Z1-C	–	2020	[88]
CO <sub>2</sub> /H <sub>2</sub>	250/20	Chemical (Experimental)	C <sub>2</sub> Z1-C	–	2020	[88]
CO <sub>2</sub> /H <sub>2</sub>	250/20	Chemical (Experimental)	C <sub>3</sub> Z1-C	–	2020	[88]
CO <sub>2</sub> /H <sub>2</sub>	–	Photochemical	–	–	2020	[89]
CO <sub>2</sub> /H <sub>2</sub>	250/65	Chemical (Simulation)	Cu–Zn–Al	99.3	2016	[90]
CO <sub>2</sub> /H <sub>2</sub>	–	Electrocatalytic	Cu-based	99.99	2018	[91]
CO <sub>2</sub> /H <sub>2</sub>	483–518/15–50	Mathematical Modelling (Anova analysis)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2017	[92]
CO <sub>2</sub> /H <sub>2</sub>	200/1	Chemical (Experimental)	Pd/Cu ratio in Pd–Cu–Zn/SiC	99	2017	[93]
CO <sub>2</sub> /H <sub>2</sub>	220/82	Simulation	CuZA	–	2020	[94]
CO <sub>2</sub> /H <sub>2</sub>	480–550/50–30	Chemical (–)	–	–	2018	[95]
CO <sub>2</sub> /H <sub>2</sub>	890/25	Chemical (–)	Pd–Cu–Zn/SiC	–	2018	[96]
CO <sub>2</sub> /H <sub>2</sub>	250/50	Chemical (Aspen Plus Simulation)	Cu/Zn/Al/Zr fibrous	100	2016	[97]



**Table 10.** (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (simulation – ASPEN Plus)	–	99.5	2016	[98]
CO <sub>2</sub> /H <sub>2</sub>	473/55	Chemical (simulation – ASPEN Plus and MATLAB)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	93.9	2019	[99]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (experiment)	Cu.ZnO	–	2016	[100]
CO <sub>2</sub> /H <sub>2</sub>	145/80	Chemical (experiment)	Ru–Macho–BH	–	2019	[101]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (experiment)	CuO–ZnO–CeO <sub>2</sub>	–	2019	[102]
CO <sub>2</sub> /H <sub>2</sub>	300/30	Chemical (experiment)	Cu/Al <sub>2</sub> O <sub>3</sub> , Cu/AlCeO and Cu/CeO <sub>2</sub>	–	2019	[103]
CO <sub>2</sub> /H <sub>2</sub>	180/50	Chemical (Simulation - Aspen Plus)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	91.7	2019	[104]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (experiment)	ZrO <sub>2</sub>	–	2019	[105]
CO <sub>2</sub> /H <sub>2</sub>	650/–	Chemical (experiment)	PdZn/TiO <sub>2</sub>	–	2018	[106]
CO <sub>2</sub> /H <sub>2</sub>	250/50	Chemical (thermodynamic model-based)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	99.8	2017	[107]
CO <sub>2</sub> /H <sub>2</sub>	508/30	Chemical (experiment)	CuCeTiO <sub>x</sub>	–	2017	[108]
CO <sub>2</sub> /H <sub>2</sub>	508/30	Chemical (experiment)	Cu/SiO <sub>2</sub>	–	2017	[108]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (experiment)	CuZnCeTi	–	2019	[109]
CO <sub>2</sub> /H <sub>2</sub>	–	Photoelectrochemical	Mono-phase Cu <sub>2</sub> O	90	2018	[110]
CO <sub>2</sub> /H <sub>2</sub>	240/30	Chemical (experiment-solvent-free routine)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2016	[111]
CO <sub>2</sub> /H <sub>2</sub>	240/30	Chemical (experiment-solvent-free routine)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2016	[111]
CO <sub>2</sub> /H <sub>2</sub>	240/30	Chemical (experiment-facile solid-state route)	CuO-ZnO-TiO <sub>2</sub> -ZrO <sub>2</sub>	–	2019	[112]

**Table 10.** (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	250/3	Chemical (experiment)	Cu/ZnO-SBA-15 (CZS_20_1)	–	2019	[113]
CO <sub>2</sub> /H <sub>2</sub>	250/3	Chemical (experiment)	Cu/ZnO/ZrO <sub>2</sub> -SBA-15 (CZZS_20_1)	–	2019	[113]
CO <sub>2</sub> /H <sub>2</sub>	–	Photocatalytic (experiment)	Porous copper/zinc bimetallic oxide catalyst	–	2020	[114]
CO <sub>2</sub> /H <sub>2</sub>	–	Chemical (experiment)	TiO <sub>2</sub> and ZrO <sub>2</sub>	–	2016	[115]
CO <sub>2</sub> /H <sub>2</sub>	270/45	Chemical (experiment)	LDH30Ga (Cu: 33.5 wt%)	–	2018	[116]
CO <sub>2</sub> /H <sub>2</sub>	270/45	Chemical (experiment)	LDH30Ga-ww (Cu: 34.3 wt%)	–	2018	[116]
CO <sub>2</sub> /H <sub>2</sub>	270/45	Chemical (experiment)	CZG5Ga (Cu: 31.9 wt%)	–	2018	[116]
CO <sub>2</sub>	–	Chemical (experiment)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2019	[117]
CO <sub>2</sub> /H <sub>2</sub>	270/50	Chemical (experiment)	Cu/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2017	[118]
CO <sub>2</sub> /H <sub>2</sub>	200/18	Chemical (experiment)	UiO-66-based	–	2019	[119]
CO <sub>2</sub> /H <sub>2</sub>	240/10	Chemical (experiment – Polyol method)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2019	[120]
CO <sub>2</sub> /H <sub>2</sub>	240/10	Chemical (experiment – Polyol method)	Cu/ZnO/CeO <sub>2</sub>	–	2019	[120]
CO <sub>2</sub> /H <sub>2</sub>	240/50	Chemical (experiment – co-precipitation microfluidic)	CuO/ZnO/ZrO <sub>2</sub> (M)	–	2016	[121]
CO <sub>2</sub> /H <sub>2</sub>	240/50	Chemical (experiment – co-precipitation at controlled pH)	CuO/ZnO/ZrO <sub>2</sub> (pH)	–	2016	[121]
CO <sub>2</sub> /H <sub>2</sub>	230/50	Chemical (experiment – precipitation/reduction method (NaHB <sub>4</sub> ))	CZZO	–	2016	[122]

**Table 10.** (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	230/50	Chemical (experiment – precipitation/reduction method (NaHB <sub>4</sub> ))	CZZ3	–	2016	[122]
CO <sub>2</sub> /H <sub>2</sub>	230/50	Chemical (experiment – precipitation/reduction method (NaHB <sub>4</sub> ))	CZZ5	–	2016	[122]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment – co-precipitation + impregnation)	10Cu <sup>-</sup> /CeO <sub>2</sub>	–	2017	[123]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment – co-precipitation + impregnation)	0.5Pd–10Cu/CeO <sub>2</sub>	–	2017	[123]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment – co-precipitation + impregnation)	2Pd–10Cu/CeO <sub>2</sub>	–	2017	[123]
CO <sub>2</sub> /H <sub>2</sub>	230/15	Chemical (experiment – Incipient wetness impregnation)	5% CuZn/rGo	–	2016	[124]
CO <sub>2</sub> /H <sub>2</sub>	230/15	Chemical (experiment – Incipient wetness impregnation)	10% CuZn/rGo	–	2016	[124]
CO <sub>2</sub> /H <sub>2</sub>	230/15	Chemical (experiment – Incipient wetness impregnation)	20% CuZn/rGo	–	2016	[124]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment – with internal cooling water)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub> (Cp)	–	2017	[125]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment – with internal cooling water)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub> (Cp)	–	2017	[125]
CO <sub>2</sub> /H <sub>2</sub>	230/10	Chemical (experiment – wetness impregnation)	CuO/ZrO <sub>2</sub> + CaO	–	2016	[126]
CO <sub>2</sub> /H <sub>2</sub>	230/10	Chemical (experiment – wetness impregnation)	Ag/CuO-ZrO <sub>2</sub>	–	2017	[127]

**Table 10.** (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	320/20	Chemical (Aspen Plus Simulation)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	99	2021	[128]
CO <sub>2</sub> /H <sub>2</sub>	30/50	Chemical (Catalytic Gas – Solid Phase Reaction)	Amide-based iridium	–	2021	[129]
CO <sub>2</sub> /H <sub>2</sub>	300/50	Chemical (Catalytic hydrogenation)	Au/In <sub>2</sub> O <sub>3</sub> –ZrO <sub>2</sub>	–	2020	[130]
CO <sub>2</sub> /H <sub>2</sub>	–	Electrochemical conversion	Pb <sub>83</sub> Cu <sub>17</sub>	–	2022	[131]
CO <sub>2</sub> /H <sub>2</sub>	300/50	Indium/cobalt-based system	Co <sub>3</sub> InC <sub>0.75</sub> and In <sub>2</sub> O <sub>3</sub>	–	2018	[132]
CO <sub>2</sub> /H <sub>2</sub>	320–450/250–350	Chemical (Catalytic hydrogenation)	Cu/ZnO/Zeolite	–	2022	[133]
CO <sub>2</sub> /H <sub>2</sub>	250/70	Chemical (Aspen Plus Simulation)	Cu/Zn/Al/Zr	–	2022	[134]
CO <sub>2</sub> /H <sub>2</sub>	230/25	Chemical (Aspen Plus Simulation)	CuO–ZnO/γ–Al <sub>2</sub> O <sub>3</sub>	–	2022	[135]
CO <sub>2</sub> /H <sub>2</sub>	250/30–70	Chemical (Aspen Plus Simulation)	Cu/Zn/Al/Zr	–	2022	[136]
CO <sub>2</sub> /H <sub>2</sub>	289/46	Chemical (Aspen Plus Simulation)	–	–	2021	[137]
CO <sub>2</sub> /H <sub>2</sub>	265/2	Chemical (Aspen Hysys Simulation with Energy Analyzer)	–	–	2016	[138]
CO <sub>2</sub> /H <sub>2</sub>	250/45	Chemical (Aspen Hysys Simulation with Energy Analyzer)	Cu/Zn/Al/Zr	99	2019	[139]
CO <sub>2</sub> /H <sub>2</sub>	200 – 300/25	Chemical (Aspen Hysys Simulation)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	99	2018	[140]
CO <sub>2</sub> /H <sub>2</sub>	227/40	Chemical (Kinetic Monte Carlo (KMC))	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2022	[141]

Table 10. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Methanol purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	25/30	Chemical (Aspen Plus Simulation and Matlab)	CZA	99.5	2022	[141]
CO <sub>2</sub> /H <sub>2</sub>	25/30	Chemical (Aspen Plus Simulation and Matlab)	CZA	99.8	2022	[141]
CO/CO <sub>2</sub> /H <sub>2</sub> O/H <sub>2</sub>	350/100	Chemical (Aspen Plus Simulation)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	–	2022	[142]
CO <sub>2</sub> /O <sub>2</sub> /H <sub>2</sub>	210/75	Chemical (Aspen Plus Simulation)	CuO/ZnO/Al <sub>2</sub> O <sub>3</sub>	98.8	2018	[143]

**Precious metal-based catalyst** Most relevant publications<sup>500</sup> agree that the decreased Pd species serve as active sites for the hydrogenation of carbon dioxide. But when it comes to the reaction mechanism, no one can agree. Based on the existing results, we may hypothesize that the nature of active sites causes this difference. The activated carbon dioxide can then be moved to the Pd surface and undergo hydrogenation to produce DME.

**Oxide-derived bifunctional catalyst** Despite increased stability, oxide-based catalysts still require improvements in DME selectivity and catalytic activity. Prior research has consistently demonstrated the critical role that oxygen vacancies play. Nevertheless, the quantity of oxygen vacancies and the catalytic activity/DME selectivity cannot be correlated. To rationally design and advance oxide-based catalysts for carbon dioxide hydrogenation to DME with improved catalytic performance, mechanistic studies on the formation/consumption of oxygen vacancies and the kinetics of the oxygen vacancies participating in elementary steps during carbon dioxide hydrogenation are therefore necessary.<sup>505</sup>

#### Catalyst for CO<sub>2</sub> conversion to polymer

The well-known catalysts used for polymer production are heterogeneous and homogeneous. For the copolymerization of carbon dioxide and propylene oxide, the catalysts for synthesizing carbon dioxide-based polymer polyol are typically chosen from double-metal cyanide and salen systems with high activity and immortal polymerization character. Depending on the catalyst, the resulting polyols exhibit various structures and features. For the alternating copolymerization of carbon

dioxide and propylene oxide to yield polymers with a carbonate linkage concentration greater than 99%, SalenCo is the perfect catalyst.<sup>506</sup> While heterogeneous catalysts for the carbon dioxide reaction with epoxides have received less attention than homogeneous catalysts up to this point, research on the latter is expanding. In particular, heterogeneous catalysts are more desirable than homogeneous catalysts due to their ease of separation from products and reutilization, especially with the growing interest in the widespread industrialization of this carbon dioxide conversion method.<sup>507</sup> At the same time, the disadvantages are often limited activity and selectivity.<sup>508</sup>

#### Catalyst for CO<sub>2</sub> conversion to FA

Solid catalysts are thought to be the most effective for this purpose due to their efficiency and possibility for recycling. Scientists have investigated the catalytic potential of numerous metal-organic frameworks (MOFs) based on Co, Sn, Mn, Ni, Bi, Hg, Cd, Pb, and Fe over time. In the production of FA, most of the iron-based catalysts reported thus far exclusively produce carbon monoxide as the primary product.<sup>509</sup>

Various studies have shown the production of formate through nano-structures of these metals, such as nanostructured Sn/SnOx thin film,<sup>510</sup> Sn or Sn oxide nanoparticles with < 5 nm,<sup>511</sup> hierarchical mesoporous SnO<sub>2</sub> nanosheets,<sup>512</sup> atomic layer deposited Sn or Sn sulfide on nanoneedle templates,<sup>513</sup> ultrathin Bi nanosheets,<sup>514</sup> and oxide-derived Pb.<sup>515</sup> Due to Hg, Cd, and Pb toxicity, most studies have mainly used Sn or Bi. The CO<sub>2</sub> reduction reaction's selectivity on different metals can be regulated by adjusting the reaction conditions to yield FA. For instance, high-pressure studies on CO<sub>2</sub> reduction reactions on W, Fe, Co, Ni, Zn, Pt, Rh, and Ir have been conducted.<sup>516</sup> Despite having lower selectivity than Sn or Bi, they nevertheless demonstrated considerable activity toward

**Table 11.** Studies on CO<sub>2</sub> to DME.

FEED	T (°C)/P (bar)	Method	Catalyst	Pathways	Purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub>	270/25	Chemical (experiment)	γ-Al <sub>2</sub> O <sub>3</sub>	Direct	–	2020	[12]
CO <sub>2</sub> /H <sub>2</sub>	260/30	Chemical (simulation)	–	Indirect	–	2017	[33]
CO <sub>2</sub> /H <sub>2</sub>	250/25	Chemical (simulation – ASPEN Plus)		Indirect	(99.6)	2016	[98]
CO <sub>2</sub> /H <sub>2</sub>	270 and 50	Chemical (experiment)	Cu.ZnO catalysts	Indirect	–	2016	[100]
CO <sub>2</sub> /H <sub>2</sub>	250/50	Chemical (simulation – Aspen Plus)	Cu/ZnO/γ-Al <sub>2</sub> O <sub>3</sub>	Indirect	(99.8)	2017	[107]
CO <sub>2</sub> /H <sub>2</sub>	230/–	Chemical (precipitation and reduction)	Cu/ZnO/ZrO <sub>2</sub>	Direct	–	2016	[122]
CO <sub>2</sub> /H <sub>2</sub> O/CH <sub>4</sub> / C <sub>2</sub> H <sub>6</sub> /C <sub>3</sub> H <sub>8</sub>	232/50 and 60	Chemical (simulation – UniSim Design R390.1)	–	Direct/Indirect	(99)	2018	[143]
CO <sub>2</sub> /H <sub>2</sub>	275/40	Chemical (simulation – UniSim Design R390.1)	–	Direct/Indirect	(99)	2019	[144]
CO <sub>2</sub> /H <sub>2</sub>	220–260/50	Chemical (experiment)	Ferrierite	Direct	–	2016	[145]
CO <sub>2</sub> /H <sub>2</sub>	200 to 260/50	Chemical (experiment)	CuZnZr–FER	Direct	–	2017	[146]
CO <sub>2</sub> /H <sub>2</sub>	260/ 30	Chemical (experiment)	CuO–Fe <sub>2</sub> O <sub>3</sub> –CeO <sub>2</sub> / HZSM-5 bifunctional	Direct	(63.1)	2016	[147]
CO <sub>2</sub> /H <sub>2</sub>	260/30	Chemical (experiment)	Cu–Fe/HZSM-5	Direct	–	2016	[147]
CO <sub>2</sub> /H <sub>2</sub> /CO	200/50	Chemical (simulation)	–	Direct	98.6	2016	[147]
CO <sub>2</sub> /H <sub>2</sub>	850/1	Chemical (simulation – Aspen Hysys)	–	Direct	99.95	2017	[148]

Table 11. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Pathways	Purity (%)	Publication year	Source
CO <sub>2</sub> /H <sub>2</sub> / CO	200 – 250/60–80	Chemical (simulation – Chemcad)	–	Direct	–	2020	[149]
CO <sub>2</sub> /H <sub>2</sub>	270/35	Chemical (experiment)	SAPO-11	Direct	–	2018	[150]
CO <sub>2</sub> /H <sub>2</sub>	270/30	Chemical (experiment)	SAPO-18	Direct	–	2016	[151]
CO <sub>2</sub> /H <sub>2</sub>	270/50	Chemical (experiment)	HSiW over	Direct	–	2016	[152]
CO <sub>2</sub> /H <sub>2</sub>	270/50	Chemical (experiment)	Mesoporous	Direct	–	2016	[152]
CO <sub>2</sub> /H <sub>2</sub>	270/50	Chemical (experiment)	Alumina	Direct	–	2016	[152]
CO <sub>2</sub> /H <sub>2</sub>	250/30	Chemical (experiment)	γ-Al <sub>2</sub> O <sub>3</sub>	Direct	–	2017	[153]
CO <sub>2</sub> /H <sub>2</sub>	270/50	Mathematical model	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub> (CZA)	–	–	2022	[154]
CO/CO <sub>2</sub> /H <sub>2</sub>	275/40	Chemical (experiment)	CuO–ZnO–ZrO <sub>2</sub> /SAPO–11	Direct	–	2021	[155]
CO/CO <sub>2</sub> /H <sub>2</sub>	250/60	Modeling and simulation	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub> HZSM-5	Direct	–	2017	[156]
CO <sub>2</sub> /H <sub>2</sub>	220–270/50	Sustainable DME synthesis—design	–	Direct	–	2016	[157]
CO <sub>2</sub> /H <sub>2</sub>	200/40	Fixed bed membrane reactor	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub> HZSM-5	Direct	–	2021	[158]
CO <sub>2</sub> /H <sub>2</sub>	260/30	Direct synthesis	Cu–ZnO–ZrO <sub>2</sub> with WO <sub>x</sub> /ZrO <sub>2</sub>	Direct	–	2018	[159]
CO <sub>2</sub> /H <sub>2</sub>	260/30	Direct synthesis	Cu–ZnO–ZrO <sub>2</sub> with WO <sub>x</sub> /ZrO <sub>2</sub>	Direct	–	2018	[160]
CO <sub>2</sub> /H <sub>2</sub>	240/50	Modeling (dual membrane reactor)	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub> HZSM-5	Direct	–	2016	[161]

Table 11. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Pathways	Purity (%)	Publication year	Source
CO/CO <sub>2</sub> /H <sub>2</sub>	275/30	Chemical (experiment)	Cu–ZnO–ZrO <sub>2</sub>	Direct	–	2018	[162]
CO <sub>2</sub> /H <sub>2</sub>	260/30	Chemical (experiment)	Cu–Fe–La/HZSM-5 and Cu–Fe–Ce/HZSM-5	Direct	–	2016	[163]
CO <sub>2</sub> /H <sub>2</sub>	275/40	Chemical simulation (Aspen Custom Modeler)	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub> HZSM-5	Direct	–	2022	[164]
CO/CO <sub>2</sub> /H <sub>2</sub>	250/50	Chemical (Experiment/Matlab)	–	Direct	–	2018	[165]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment)	CZZH-300	Direct	–	2016	[166]
CO <sub>2</sub> /H <sub>2</sub>	230/30	Chemical (experiment)	CZZH-400	Direct	–	2016	[166]
CO/CO <sub>2</sub> /H <sub>2</sub>	305/70	Chemical (experiment)	CuO–ZnO–ZrO <sub>2</sub> @SAPO-11	Direct	–	2019	[167]
CO <sub>2</sub> /H <sub>2</sub>	80/35	Chemical simulation (Aspen Plus/Matlab)	Cu–ZnO/Al <sub>2</sub> O <sub>3</sub>	Direct	99.99	2019	[168]

formate formation. Pd produced a substantial amount of CO, but it also performed well in the synthesis of FA.<sup>517,518</sup>

Various methods for producing FA include electrochemical, photochemical, and hydrogenation. In contrast to the other methods, the electrochemically facilitated carbon dioxide conversion to FA requires lower temperatures and pressures, lowering operating and production costs. This explains why most of the CO<sub>2</sub> conversion to FA studies are via the electrochemical method. Nevertheless, there is still a limit to the metal catalysts' selectivity when converting carbon dioxide into certain compounds.<sup>519</sup> The current photocatalytic system has several drawbacks that prevent it from being used in industrial settings. These drawbacks include low visible light consumption, rapid charge recombination, and poor photogenerated electron and hole migration capabilities.<sup>520</sup>

#### Catalyst for CO<sub>2</sub> conversion to urea

The conventional urea production process is an energy- and carbon-intensive technology that contradicts the idea of carbon neutrality. Electrocatalytic urea manufacturing is a promising and sustainable method since, fortunately, using renewable

energy in electrochemical synthesis has demonstrated considerable potential for producing high-value nitrogen compounds. However, its large-scale industrial growth is limited by its poor yield and Faraday efficiency, as well as the uncertain process of C–N bond formation. Researchers are looking for electrocatalysts with improved performance.<sup>521</sup> The various categories of catalysts used to produce urea are<sup>521</sup> Metal and metal alloys, Metal compounds, and Metal–organic compounds. Electrocatalytic synthesis is a promising technique with the potential to produce urea more efficiently and sustainably. Using an electrocatalyst to speed up chemical reactions can save energy by removing the high pressure and temperature requirement during electrocatalytic synthesis.<sup>521</sup> However, there are still several difficulties with electrocatalytic urea production. First, urea is the final target product. Secondly, the creation of novel electrocatalysts is the most significant obstacle. Thirdly, a thorough and in-depth investigation of the synthesis process is the component of mutual reinforcement.<sup>521</sup> According to one study, electrocatalytic urea synthesis requires a Faraday efficiency of 56.2% to compete with the conventional urea synthesis industry at an average battery voltage of 2.7 V.<sup>522</sup> PdCu/CBC has achieved the highest Faraday efficiency record of 69.1%.<sup>523</sup>



Table 12. Studies of CO<sub>2</sub> to polymer.

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /alcohols	265/92	Chemical (experiment)	CeO <sub>2</sub> based	Linear-, cyclic- and poly-carbonates	2020	[13]
CO <sub>2</sub>	135/20	Chemical (simulation-Aspen Plus)	–	polyol	2017	[170]
CO <sub>2</sub>	50/22	Chemical (experiment)	Comb-Shaped Metallic Oligomer	poly(ether carbonate)	2021	[171]
CO <sub>2</sub> /Propylene oxide	70/50	Chemical (experiment)	Propylene oxide	Poly(propylene carbonates)	2019	[172]
CO <sub>2</sub> /Limonene oxide	250–280/15	Chemical (experiment)	Al(III) aminotriphenolate complex/PPNCI (PPN = bis(triphenyl) phosphine-ammonium)	Terpolymer	2016	[173]
CO <sub>2</sub> /Limonene oxide	20/11	Chemical (experiment)	–	Polycarbonates	2016	[174]
CO <sub>2</sub> /methanol	160/48	Chemical (experiment)	ZrO <sub>2</sub>	Dimethyl carbonates	2018	[175]
CO <sub>2</sub> /methanol	363/13	Chemical (experiment)	Cu-Ni/AC	Dimethyl carbonates	2020	[176]
CO <sub>2</sub> /1,4-Butanediol	150/82	Chemical (experiment)	ceria nanorod	Poly(butylene carbonates)	2020	[177]
CO <sub>2</sub> /methanol	130/16	Chemical (experiment)	SnO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	Dimethyl carbonates	2016	[178]
CO <sub>2</sub> /diols	130/50	Chemical (experiment)	CeO <sub>2</sub> /2-furonitrile	Polycarbonates	2019	[179]
CO <sub>2</sub> /anilines/branched alcohols	150/50	Chemical (experiment)	CeO <sub>2</sub> /2-cyanopyridine	alkyl N-arylcarbamates	2019	[180]
CO <sub>2</sub>	170/30	Chemical (experiment)	ceria-supported	Diethyl-carbonates	2018	[181]
CO <sub>2</sub> /methanol	110/50	Chemical (experiment)	Fe-Zr mixed oxides	Dimethyl carbonates	2017	[182]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /glycerol carbonylation	150/40	Chemical (experiment)	CeO <sub>2</sub>	Glycerol carbonate	2016	[183]
CO <sub>2</sub> /methanol	100/30	Chemical (experiment)	CeO <sub>2</sub>	Dimethyl carbonates	2020	[184]
CO <sub>2</sub> /methanol	110/20	Chemical (experiment)	Bimetallic Cu–Ni/ZIF-8 MOF	Dimethyl carbonates	2017	[185]
CO <sub>2</sub> /methanol with 2-cyano-pyridine	120/30	Chemical (experiment)	CeO <sub>2</sub>	Dimethyl carbonates	2018	[186]
CO <sub>2</sub> /methanol with over yttrium oxide	90/80	Chemical (experiment)	–	Dimethyl carbonates	2020	[187]
CO <sub>2</sub>	140/65	Chemical (experiment)	Ce <sub>x</sub> Zr <sub>1-x</sub> O <sub>2</sub>	Dimethyl carbonates	2018	[188]
CO <sub>2</sub> /methanol	140/120	Chemical (experiment)	Metal–organic frameworks MOF-808-X	Dimethyl carbonates	2019	[189]
CO <sub>2</sub> /methanol	130/12	Chemical (experiment)	Hydrophobic Ce/SBA-15	Dimethyl carbonates	2018	[190]
CO <sub>2</sub> /epoxides	80/25	Chemical (experiment)	Cu-MOF1	Cyclic carbonate	2019	[191]
CO <sub>2</sub> /epoxides	Room Temp./1	Chemical (experiment)	MOF1	Cyclic carbonate	2019	[192]
CO <sub>2</sub> /epoxides	50/4	Chemical (experiment)	MOF-5	Cyclic carbonate	2019	[193]
CO <sub>2</sub> /epoxides	60/1	Chemical (experiment)	Ni-MOF-1	Cyclic carbonate	2019	[194]
CO <sub>2</sub> /epoxides	50/12	Chemical (experiment)	MOF-5-MIX	Cyclic carbonate	2019	[195]
CO <sub>2</sub> /epoxides	60/12	Chemical (experiment)	UiO-66	Cyclic carbonate	2019	[196]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /epoxides	60/12	Chemical (experiment)	Cu-BTC (BTC = benzene-1,3,5-tricarboxylate)	Cyclic carbonate	2019	[196]
CO <sub>2</sub> /epoxides	60/12	Chemical (experiment)	Cu-BTC/UIO-66	Cyclic carbonate	2019	[196]
CO <sub>2</sub> /epoxides	60/12	Chemical (experiment)	UIO-66/Cu-BTC	Cyclic carbonate	2019	[196]
CO <sub>2</sub> /epoxides	120/15	Chemical (experiment)	M-UTSA-16	Cyclic carbonate	2018	[197]
CO <sub>2</sub> /epoxides	120/20	Chemical (experiment)	N <sub>4</sub> -Schiff base ligand (H <sub>2</sub> CyTs)	Cyclic carbonate	2018	[198]
CO <sub>2</sub> /epoxides	85/6	Chemical (experiment)	SAPO-34	Cyclic carbonate	2017	[199]
CO <sub>2</sub> /epoxides	31/73.8	Chemical (experiment)	MeNSBA-15	Cyclic carbonate	2018	[200]
CO <sub>2</sub> /epoxides	120/16	Chemical (experiment)	Ti-mSiO <sub>2</sub> (C)	Cyclic carbonate	2019	[201]
CO <sub>2</sub> /epoxides	80/10	Chemical (experiment)	Zn-SBA-15	Cyclic carbonate	2016	[202]
CO <sub>2</sub> /epoxides	130/3	Chemical (experiment)	NH <sub>3</sub> -Zn/SBA-15	Cyclic carbonate	2016	[203]
CO <sub>2</sub> /epoxides	140/1	Chemical (experiment)	ZnHZSM-5	Cyclic carbonate	2018	[204]
CO <sub>2</sub> /epoxides	110/20	Chemical (experiment)	SBA-15 (TEA/SBA-15)	Cyclic carbonate	2018	[205]
CO <sub>2</sub> /epoxides	70/10	Chemical (experiment)	TBAI	Cyclic carbonate	2018	[206]
CO <sub>2</sub> /epoxides	50/10	Chemical (experiment)	Zr-based MOF	Cyclic carbonate	2018	[207]
CO <sub>2</sub> /propylene oxide	25/1	Chemical (experiment)	Cu-MOF (NTU-180)	Propylene carbonate	2019	[208]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /epoxides	80/1	Chemical (experiment)	UiO-66@Fe <sub>3</sub> O <sub>4</sub> @SiO <sub>2</sub>	Cyclic carbonate	2016	[209]
CO <sub>2</sub> /epoxides	80/12	Chemical (experiment)	ZIF-95	Cyclic carbonate	2017	[210]
CO <sub>2</sub> /epoxides	80/20	Chemical (experiment)	Gd-MOF	Cyclic carbonate	2017	[211]
CO <sub>2</sub> /epoxides	80/20	Chemical (experiment)	TBAB	Cyclic carbonate	2017	[212]
CO <sub>2</sub> /epoxides	80/20	Chemical (experiment)	TBAB	Cyclic carbonate	2017	[213]
CO <sub>2</sub> /epoxides	80/10	Chemical (experiment)	MOF-Zn-1	Cyclic carbonate	2018	[214]
CO <sub>2</sub> /epoxides	80/11	Chemical (experiment)	TBAB	Cyclic carbonate	2018	[215]
CO <sub>2</sub> /propylene oxide	100/10	Chemical (experiment)	TBABr	Cyclic carbonate	2019	[216]
CO <sub>2</sub> /styrene oxide	130/25	Chemical (experiment)	La/Zr	Styrene carbonate	2017	[217]
CO <sub>2</sub>	130/30	Chemical (experiment)	Li-MgO	Cyclic carbonate	2018	[218]
CO <sub>2</sub> /epoxides	130/12	Chemical (experiment)	Bis-ammonium@ polystyrene	Cyclic carbonate	2016	[219]
CO <sub>2</sub> /epoxides	30/1	Chemical (experiment)	Metalated porous porphyrin polymer	Cyclic carbonate	2016	[220]
CO <sub>2</sub> /epoxides	100/8	Chemical (experiment)	Imidazolium based polymer supported ionic liquid	Cyclic carbonate	2016	[221]
CO <sub>2</sub> /epoxides	60/1	Chemical (experiment)	Bifunctional quaternary phosphonium salt catalyst	Cyclic carbonate	2016	[222]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /epoxides	50/50	Chemical (experiment)	Chiral Co(II) complexes	Cyclic carbonate	2016	[223]
CO <sub>2</sub> /epoxides	100/10	Chemical (experiment)	–	Cyclic carbonate	2018	[224]
CO <sub>2</sub> /epoxides	120/17	Chemical (experiment)	B <sub>2</sub> O <sub>3</sub>	Cyclic carbonate	2019	[225]
CO <sub>2</sub> /epoxides	170/70	Chemical (experiment)	CeZrLa mixed-oxide	Propylene carbonate	2019	[226]
CO <sub>2</sub> /epoxides	90/20	Chemical (experiment)	P-C <sub>3</sub> N <sub>4</sub>	Cyclic carbonate	2016	[227]
CO <sub>2</sub> /styrene oxide	120/30	Chemical (experiment)	GO	Cyclic carbonate	2018	[228]
CO <sub>2</sub> /epoxides	100/10	Chemical (experiment)	Oxidized Biochar	Cyclic carbonate	2019	[229]
CO <sub>2</sub> /epoxides	120/10	Chemical (experiment)	Zn-based	Propylene carbonate	2019	[230]
CO <sub>2</sub> /epoxides	100/16	Chemical (experiment)	NBu <sub>4</sub> Br	Porous-organic polymers	2016	[231]
CO <sub>2</sub> /epoxides	120/1	Chemical (experiment)	Imidazolium- and Triazine-	Cyclic carbonate	2017	[232]
CO <sub>2</sub> /epoxides	160/20	Chemical (experiment)	Porous polymeric hollow fibers	polyurethane	2017	[233]
CO <sub>2</sub> /epoxides	80/10	Chemical (experiment)	Porous aromatic polymers functionalized with ethylenediamine	Cyclic carbonate	2017	[234]
CO <sub>2</sub> /epoxides	150/35	Chemical (experiment)	Nanocrystalline zeolite	Cyclic carbonate	2017	[235]
CO <sub>2</sub> /epoxides	80/7	Chemical (experiment)	Synthesizable zeolitic imidazolium framework	Cyclic carbonate	2018	[236]
CO <sub>2</sub>	304/73.8	Chemical	–	Polymer	2020	[237]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /epoxides	150/50	Chemical (experiment)	Alkali metal salt	Cyclic carbonate	2018	[238]
CO <sub>2</sub> /orthoester	160/50	Chemical (experiment)	CeO <sub>2</sub>	Diethyl carbonate	2022	[239]
CO <sub>2</sub> /diols	200/75	Chemical (experiment)	CeO <sub>2</sub>	Polycarbonate diols	2021	[240]
CO <sub>2</sub> /ethanol	120/40	Chemical (experiment)	CeO <sub>2</sub>	Diethyl carbonate	2021	[241]
CO <sub>2</sub> /ethanol	100/1	Chemical (experiment)	CeO <sub>2</sub> .8Zr0.2O2	Diethyl carbonate	2017	[242]
CO <sub>2</sub> /methanol	120/1	Chemical (experiment)	CeO <sub>2</sub>	Dimethyl carbonate	2021	[243]
CO <sub>2</sub> /methanol	160/24	Chemical (experiment)	Monolithic Zn <sub>x</sub> Ce <sub>1-x</sub> O <sub>2</sub>	Dimethyl carbonate	2020	[244]
CO <sub>2</sub> /methanol	180 50	Chemical (experiment)	Calcium carbide	Glycerol carbonate and cyclic carbonate	2020	[245]
CO <sub>2</sub> /methanol	130/4	Chemical (experiment)	Zr/Ce/Cu-based nanocomposites	Dimethyl carbonate	2022	[246]
CO <sub>2</sub> /methanol	140/22	Chemical (experiment)	Ti0.04Ce0.96O2	Dimethyl carbonate	2018	[247]
CO <sub>2</sub> /epoxides	150/50	Chemical (experiment)	CeO <sub>2</sub> -spindles	Dimethyl carbonate	2016	[248]
CO <sub>2</sub> /epoxides	160/24	Chemical (experiment)	CuNi@POP-PPh <sub>3</sub>	Dimethyl carbonate	2019	[249]
CO <sub>2</sub> /methanol	32/10	Chemical (experiment)	Zr/Ce/Cu-based nanocomposites	Dimethyl carbonate	2022	[250]
CO <sub>2</sub> /methanol	140/30	Chemical (experiment)	–	Dimethyl carbonate	2021	[251]
CO <sub>2</sub> /ethanol	200/30	Chemical (experiment)	CeO <sub>2</sub> and zeolite	Diethyl carbonate	2020	[252]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /methanol	120/30	Chemical (experiment)	IL-EMCOMONS-500	Dimethyl carbonate	2020	[253]
CO <sub>2</sub> /epoxides/methanol	110/6	Chemical (experiment)	–	Dimethyl carbonate	2019	[254]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bmim][Cl]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bmim][BF <sub>4</sub> ]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bmim][PF <sub>6</sub> ]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[emim][BF <sub>4</sub> ]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[emim][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[mbmim][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[dmbmim][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bpy][Cl]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bpy][BF <sub>4</sub> ]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[bpy][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[epy][BF <sub>4</sub> ]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[epy][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]
CO <sub>2</sub> /methanol	170/40	Chemical (experiment)	[dmbpy][Tf <sub>2</sub> N]	Dimethyl carbonate	2017	[255]

Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][OMs] <sub>3</sub>	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][NTf <sub>2</sub> ] <sub>3</sub>	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][Br] <sub>3</sub>	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][OMs] <sub>3</sub> /DBU	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][NTf <sub>2</sub> ] <sub>3</sub> /DBU	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	130/75	Chemical (experiment)	[GLY(mim) <sub>3</sub> ][Br] <sub>3</sub> /DBU	Dimethyl carbonate	2016	[256]
CO <sub>2</sub> /methanol	25/10	Chemical (experiment)	[C <sub>1</sub> C <sub>4</sub> Im][HCO <sub>3</sub> ] <sup>-</sup> + CsCO <sub>3</sub>	Dimethyl carbonate	2017	[257]
CO <sub>2</sub> /methanol	25/10	Chemical (experiment)	[C <sub>1</sub> C <sub>4</sub> Im][HCO <sub>3</sub> ] <sup>-</sup> + KHCO <sub>3</sub>	Dimethyl carbonate	2017	[257]
CO <sub>2</sub> /methanol	25/10	Chemical (experiment)	[C <sub>1</sub> C <sub>6</sub> Im][HCO <sub>3</sub> ] <sup>-</sup> + CsCO <sub>3</sub>	Dimethyl carbonate	2017	[257]
CO <sub>2</sub> /methanol	150/200	Chemical (experiment)	Triorganotin(IV)	Dimethyl carbonate	2018	[258]
CO <sub>2</sub> /methanol	120/10	Chemical (experiment)	Binary ionic liquid/base	Cyclic carbonate	2019	[259]
CO <sub>2</sub> /methanol	170/50	Chemical (experiment)	CeO <sub>2</sub>	Dimethyl carbonate	2019	[260]
CO <sub>2</sub> /methanol	197/1	Chemical (experiment)	–	Dimethyl carbonate	2018	[261]
CO <sub>2</sub> /methanol	120/50	Chemical (experiment)	Ce <sub>3</sub> -NPs/Co <sub>7</sub> -NSs	Dimethyl carbonate	2022	[262]
CO <sub>2</sub> /methanol	140/35	Chemical (experiment)	Ceria nanorod	Dimethyl carbonate	2022	[263]



Table 12. (continued)

FEED	T (°C)/P (bar)	Method	Catalyst	Final products	Publication year	Source
CO <sub>2</sub> /methanol	120/30	Chemical (experiment)	–	Dimethyl carbonate	2017	[264]
CO <sub>2</sub> /methanol	120/1	Chemical (experiment)	Ce/Ca	Dimethyl carbonate	2017	[265]
CO <sub>2</sub> /methanol	120–160/70–80	Chemical (experiment)	Ce <sub>x</sub> Zr <sub>1-x</sub> O <sub>2</sub>	Dimethyl carbonate	2018	[266]
CO <sub>2</sub> /methanol	150/5	Chemical (experiment)	Zirconium and cerium	Dimethyl carbonate	2017	[267]
CO <sub>2</sub> /methanol	150/6	Chemical (experiment)	CeO <sub>2</sub> -ZrO <sub>2</sub>	Dimethyl carbonate	2022	[268]
CO <sub>2</sub> /methanol	140/30	Chemical (experiment)	Ceria nanostructured	Dimethyl carbonate	2020	[269]
CO <sub>2</sub> /methanol	140/64	Chemical (experiment)	IL/DBU/SmOCl	Dimethyl carbonate	2016	[270]
CO <sub>2</sub> /methanol	60/2.5	Chemical (experiment)	–	Dimethyl carbonate	2021	[271]
CO <sub>2</sub> /methanol	140/80	Chemical (experiment)	–	Dimethyl carbonate	2021	[272]

**Table 13.** Studies of CO<sub>2</sub> to FA.

T (°C)/P(Bar)	Method	Cathode/anode/ electro-catalyst	Current densities (mA cm <sup>-2</sup> )	FA production rate (mmol/ m <sup>2</sup> s <sup>-1</sup> )	Publication year	Source
25/1	Electrochemical	Mp-SnO <sub>2</sub> NS	15	–	2019	[14]
Ambient temp./50	Electrochemical	Sn Plates/Ir-MMO	~ 100	2(4)	2019	[273]
Ambient temp./1	Electrochemical	Sn/C-GDE/Ir-MMO	200	4.38	2017	[274]
–	Electrochemical	Sustainion anion membrane	140	–	2017	[275]
Ambient temp./1	Electrochemical	Sn/C-GDE/IrO <sub>2</sub>	140	6.8	2017	[275]
Ambient temp./1	Electrochemical	IrO <sub>2</sub>	450	–	2020	[276]
Ambient temp./73	Electrochemical	–	–	75	2019	[277]
Ambient temp./30	Electrochemical	Sn plate/Ti/IrO <sub>2</sub> -Ta <sub>2</sub> O <sub>5</sub>	50	2.1	2018	[278]
20/1	Electrochemical	Sn/Bi-based electrocatalyst	300	1.15	2020	[279]
20/1	Electrochemical	Sn/Bi-based electrocatalyst	300	5.61	2020	[279]
60/1	Electrochemical	SnO <sub>2</sub> electrocatalyst	500	–	2020	[280]
20/1	Electrochemical	SnO <sub>2</sub> pNWs	4.8	–	2017	[281]
–	Electrochemical	SnO <sub>2</sub> nanoparticles	147	46	2018	[282]
–	Electrochemical	SnO <sub>2</sub> nanoparticles (<5 nm)	145	64	2018	[282]
–	Electrochemical	Nitrogen-doped graphene	7.5	–	2016	[283]
40/1	Electrochemical	Electrodeposited Sn particles (~ 500 nm)	~ 7.6	–	2016	[283]
20/1	Electrochemical	Electrodeposited Sn (~ 1 μm thick)	~ 10	–	2016	[284]
500/1	Electrochemical	Sn quantum sheets/GO	18.8	–	2017	[285]
500/1	Electrochemical	Tin quantum sheets (~ 5 nm)	21.1	–	2017	[285]
25/1	Electrochemical	Tin oxide SnO <sub>2</sub> nanoparticle	385 ± 19	14.9 ± 0.8	2019	[286]
25/1	Electrochemical	Tin (Sn) nanoparticle	214 ± 6	7.4 ± 0.6	2019	[286]

**Table 13.** (continued)

T (°C)/P(Bar)	Method	Cathode/anode/ electro-catalyst	Current densities (mA cm <sup>-2</sup> )	FA production rate (mmol/m <sup>2</sup> s <sup>-1</sup> )	Publication year	Source
27/1	Electrochemical	Sc- and Ti-porphyrin-like graphene	–	–	2021	[287]
200/1	Electrochemical	Chain-like mesoporous SnO <sub>2</sub>	13	–	2019	[288]
–	Electrochemical	sulfur-modulated tin (Sn(S))	55	–	2017	[289]
500/1	Electrochemical	Sn(S)/Au	51.1	–	2017	[289]
20/15–30	Electrochemical	Sn cathode	90	–	2016	[290]
100/1	Electrochemical	SnO <sub>x</sub> @multiwalled carbon nanotube COOH	8.5	–	2019	[291]
500/1	Electrochemical	Wire-in-tube SnO <sub>2</sub>	–	–	2018	[292]
25/1	Electrochemical	Sn-CF1000	11	–	2018	[293]
25/1		SnS <sub>2</sub> /rGO	11.7	–	2016	[294]
500/1	Electrochemical	Electrodeposited Bi dendrites	14.6	–	2016	[295]
25/1	Electrochemical	Bi nanoflake	~1	–	2017	[296]
25/1	Electrochemical	Bi dendrite	2.4	–	2017	[297]
25/1	Electrochemical	Bi nanosheets	16.5	–	2018	[298]
25/1	Electrochemical	Ultrathin Bi nanosheets	12.5	–	2018	[299]
25/1	Electrochemical	Few-layer bismuth subcarbonate nanosheet	8.5	–	2018	[299]
25/1	Electrochemical	Sulfide-derived Bi	4.2	–	2018	[299]
25/1	Electrochemical	P-orbital localized–Bi	54.1	–	2018	[300]
70/1	Electrochemical	BiOx/C	1.35	–	2018	[301]
24/1	Electrochemical	Bi–PMo nanosheets	30	–	2019	[302]
25/1	Electrochemical	Bi <sub>2</sub> O <sub>3</sub> –NGQDs	16.6	–	2018	[303]

**Table 13.** (continued)

T (°C)/P(Bar)	Method	Cathode/anode/ electro-catalyst	Current densities (mA cm <sup>-2</sup> )	FA production rate (mmol/m <sup>2</sup> s <sup>-1</sup> )	Publication year	Source
20 – 25/1	Electrochemical	Mp-Bi	15	–	2018	[304]
25/1	Electrochemical	NTD-Bi	42	–	2019	[305]
25/1	Electrochemical	Hp-in catalyst	67.5	–	2019	[306]
25/1	Electrochemical	Sulfur-Doped Indium	58.9	–	2019	[307]
25/1	Electrochemical	Dendritic Indium foams	6	–	2018	[308]
25/1	Electrochemical	Co <sub>3</sub> O <sub>4</sub> nanofibers	0.5	–	2018	[309]
15/60	Electrochemical	Sn NPs (Sn/C-GDEs)/ DSA/O <sub>2</sub> (Ir-MMO on Pt)	200	4.38	2018	[310]
15/60	Electrochemical	Sn NPs (Sn/C-GDEs)/ IrO <sub>2</sub> on Toray paper	140	2.22	2018	[310]
15/ 60	Electrochemical	Sn NPs (Sn/C-GDEs)/ IrO <sub>2</sub> on Toray paper	140	4.63	2018	[310]
220/1	Electrochemical	Ultrathin Co <sub>3</sub> O <sub>4</sub> (1.72 nm)	0.68	–	2016	[311]
220/1	Electrochemical	Partially oxidized atomic cobalt	~ 10	–	2016	[311]
	Electrochemical	Cu-CDots nanocorals	~ 4.2	–	2016	[312]
	Electrochemical	Pd catalysts	22	–	2016	[313]
70	Electrochemical	CF-CO <sub>2</sub> R	51.7	–	2018	[314]
25/1	Electrochemical	Pd–Sn alloy	–	–	2017	[315]
25/1	Electrochemical	Tiny rod-shaped Sn	–	–	2018	[316]
25/1	Electrochemical	Sn/CNT-Agls	32.9	82.7	2017	[317]

### Catalyst for CO<sub>2</sub> conversion to syngas

The various categories of catalysts used to produce Syngas are primarily homogeneous and heterogeneous. Because of their accessibility and low cost, non-noble metal-based catalysts like nickel (Ni) and cobalt (Co) were frequently considered

for industrial-scale application.<sup>524</sup> The addition of promoters was analyzed to support the catalyst's catalytic activity and prevent catalyst deactivation due to carbon deposition. Nonetheless, the prior research was primarily concerned with characterizing the catalysts' surfaces to synthesize syngas. The

**Table 14.** Studies on CO<sub>2</sub> to urea.

FEED	T (°C)/P (bar)	Method	Catalyst	Urea formation (mmol g <sup>-1</sup> h <sup>-1</sup> )	Faradaic efficiency (%)	Yield (%)	Publication year	Source
CO <sub>2</sub> /N <sub>2</sub> D/O <sub>2</sub> /H <sub>2</sub> O	178/1	Chemical (Simulation-Aspen Hysys)	–	–	–	–	2020	[318]
CO <sub>2</sub>	25/1	Electrocatalytic	Nano-FeTiO <sub>3</sub> surface	–	–	–	2017	[319]
CO <sub>2</sub> /N <sub>2</sub>	40/1	Electrochemical Reduction	Te–Pd NCs	–	10.2	82.3	2020	[320]
CO <sub>2</sub> /N <sub>2</sub> (N <sub>2</sub> CO <sub>2</sub> RR)	25/1	Photoelectrochemical reduction	–	98.5	22.7	–	2022	[321]
CO <sub>2</sub> /diamine	150/80	ZnO/KF/Al <sub>2</sub> O <sub>3</sub>	ZnO/KF/Al <sub>2</sub> O <sub>3</sub>	–	–	–	2020	[322]
CO <sub>2</sub> /amines	150/30	Electrochemical	Y <sub>2</sub> (C <sub>2</sub> O <sub>4</sub> ) <sub>3</sub>	–	–	–	2016	[323]
CO <sub>2</sub> /amines	80/50	Chemical (Synthesis)	–	–	–	–	2017	[324]
CO <sub>2</sub>	170/40	Chemical (experiment)	KATriz	–	–	–	2018	[325]
CO <sub>2</sub> /N <sub>2</sub> /NH <sub>3</sub> /O <sub>2</sub> /Ar	100/160	Chemical (simulation-Stamicarbon process)	–	–	–	–	2018	[326]
CO <sub>2</sub> /NH <sub>3</sub>	275/100	Chemical (simulation-looping process)	–	–	–	–	2016	[327]
CO <sub>2</sub> /NH <sub>3</sub>	180/150	Chemical (Simulation-Aspen Hysys)	–	–	–	–	2016	[327]

techno-economic sustainability of homogeneous catalysts for industrial production will require additional evaluations.<sup>525</sup>

#### Catalyst for CO<sub>2</sub> conversion to methane

CO<sub>2</sub> methanation over a variety of metal catalysts, Ru,<sup>526</sup> Ni,<sup>527</sup> Co,<sup>528</sup> and Fe,<sup>529</sup> has been studied for effective and economical production. There are two types of catalytic systems:

homogeneous and heterogeneous.<sup>525</sup> Controlling single-site catalyst performance during design and synthesis has proven to be a difficult part of developing homogeneous catalysts.<sup>525</sup> The assessments reveal that electrocatalytic homogeneous conversion of carbon dioxide to fuel is still under development for optimizing catalyst characteristics and operating conditions for larger applications. Furthermore, recent studies mainly evaluated

**Table 15.** Studies of CO<sub>2</sub> to building materials.

FEED and blender-type	Technologies	Operating condition (°C/bar)	Products	Publication year	Source
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	–	2021	[329]
CO <sub>2</sub>	Carbonation	45/6.5	Portland cement-based concrete	2022	[330]
CO <sub>2</sub>	CO <sub>2</sub> Curing	29/297	–	2017	[331]
CO <sub>2</sub>	–	45/75	–	2016	[332]
CO <sub>2</sub>	CO <sub>2</sub> Curing	10/7	Ultra-high-performance concrete (UHPC)	2022	[333]
CO <sub>2</sub>	CO <sub>2</sub> based-cements	27/1	–	2016	[334]
CO <sub>2</sub>	CO <sub>2</sub> based-cements	23–25/1	–	2017	[335]
CO <sub>2</sub>	Carbonation	40/30	–	2022	[336]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/36	Artificial aggregates	2022	[337]
CO <sub>2</sub>	Carbonation	80/0.03–0.1	–	2022	[338]
CO <sub>2</sub>	Carbonation	20/117.3	Calcite	2016	[339]
CO <sub>2</sub>	Carbonation	25/1	–	2021	[340]
CO <sub>2</sub>	Carbonation	25/1	Calcite	2017	[341]
CO <sub>2</sub>	Carbonation	150/30	Calcite	2018	[342]
CO <sub>2</sub>	Carbonation	70/1	Calcite	2016	[343]
CO <sub>2</sub>	Carbonation	25/1	Calcite	2016	[344]
CO <sub>2</sub>	Carbonation	50/1	Calcite	2018	[345]
CO <sub>2</sub>	CO <sub>2</sub> Curing	22/2	Engineered cementitious composite	2018	[346]
CO <sub>2</sub>	Carbonation	25/1	Fly ash concrete	2016	[347]
CO <sub>2</sub>	CO <sub>2</sub> Curing	20/1	Cement pastes	2020	[348]

**Table 15.** (continued)

FEED and blender-type	Technologies	Operating condition (°C/bar)	Products	Publication year	Source
CO <sub>2</sub>	CO <sub>2</sub> Curing	23/0.1	Curing Portland cement-based materials	2018	[349]
CO <sub>2</sub>	CO <sub>2</sub> Curing	23/0.1	Hardening of cement pastes	2019	[350]
CO <sub>2</sub>	Experimental Carbonation	40/1	Recycled concrete aggregates	2021	[351]
CO <sub>2</sub>	Carbonation	25/(0, 7.5 and 15)	Concrete	2016	[352]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	100/1–5	Cyclic Carbonates	2020	[353]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	35–38/1	Concrete	2016	[354]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements and CO <sub>2</sub> Curing	22/0.1–50	Concrete	2020	[355]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Concrete	2018	[356]
CO <sub>2</sub>	CO <sub>2</sub> Curing	20/1	Concrete	2018	[357]
CO <sub>2</sub>	Carbonation	25/1	Concrete	2021	[358]
CO <sub>2</sub>	–	25/1	Aggregates	2022	[359]
CO <sub>2</sub>		25/1	Building materials	2021	[360]
CO <sub>2</sub>	Carbonation	25/2,4,6	Concrete	2020	[361]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Concrete	2021	[362]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Concrete	2021	[329]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	–	2022	[363]
CO <sub>2</sub>	CO <sub>2</sub> Curing	23/1	Concrete	2021	[364]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Concrete	2016	[365]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/10	–	2020	[366]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	25/1	Cement	2020	[367]

Table 15. (continued)

FEED and blender-type	Technologies	Operating condition (°C/bar)	Products	Publication year	Source
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	25/244	Concrete	2022	[368]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	25/163	Concrete	2022	[368]
CO <sub>2</sub>	CO <sub>2</sub> Based-Cements	25/261	Concrete	2022	[368]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Cement and concrete	2021	[369]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Concrete	2019	[370]
CO <sub>2</sub>	CO <sub>2</sub> cement-based	25/1	SCMs	2018	[371]
CO <sub>2</sub> and solid wastes	CO <sub>2</sub> Curing	20/12	Concrete	2022	[372]
CO <sub>2</sub> and saturated brine	Carbonation	120/280	Cement	2019	[373]
CO <sub>2</sub> and industrial wastes (fly ash, blast furnace slag, and red mud)	CO <sub>2</sub> Curing	25/25	Concrete	2019	[374]
CO <sub>2</sub> and fly ashes	Carbonation	75/350	Ordinary Portland cement (OPC)	2018	[375]
CO <sub>2</sub> and fly ashes	Carbonation	20/1	–	2016	[376]
CO <sub>2</sub> and fly ashes	Carbonation	30/1	–	2017	[377]
Fuel ash and CO <sub>2</sub>	CO <sub>2</sub> Curing	20/1	Magnesium oxysulfate cement	2020	[378]
Fuel ash and CO <sub>2</sub>	CO <sub>2</sub> Curing	25/1	Magnesium oxychloride cement (MOC)	2016	[379]
CO <sub>2</sub>	CO <sub>2</sub> Curing	23/1	Nano-calcium carbonate	2018	[380]
CO <sub>2</sub>	CO <sub>2</sub> cement-based	80–150 and 600–800/3 and 4	Calcium sulfoaluminate cement	2021	[381]
CO <sub>2</sub>	CO <sub>2</sub> cement-based	25/1	Cement	2019	[382]
CO <sub>2</sub>	CO <sub>2</sub> cement-based	25/1	Cement	2016	[383]
CO <sub>2</sub>	CO <sub>2</sub> Curing	28/6	Aggregate and prepared concrete	2020	[384]



Table 15. (continued)

FEED and blender-type	Technologies	Operating condition (°C/bar)	Products	Publication year	Source
CO <sub>2</sub>	CO <sub>2</sub> Curing	20–80/546	Concrete blocks	2016	[385]
CO <sub>2</sub>	CO <sub>2</sub> Curing	23/156	Construction materials	2019	[386]
CO <sub>2</sub>	Carbonation	20/1	Concrete	2018	[387]
CO <sub>2</sub> and slurry waste	Carbonation	260/300	Concrete	2016	[388]
CO <sub>2</sub>	CO <sub>2</sub> Curing	25/0.1 and 4	Concrete	2016	[389]
CO <sub>2</sub>	Carbonation	29/0.7	Cement	2018	[390]
CO <sub>2</sub>	CO <sub>2</sub> Curing	20/1	CaCO <sub>3</sub>	2016	[391]
CO <sub>2</sub> , concrete slurry waste (CSW), and fine incineration bottom ash (IBA)	CO <sub>2</sub> Curing	60/0.1	Cold-bonded lightweight aggregates (CBLAs)	2020	[392]
CO <sub>2</sub>	CO <sub>2</sub> cement-based	115/7	Carbonate aggregates	2017	[393]
CO <sub>2</sub>	Carbonation	25/37.4	MgO cement and MgO-Portland binary cement	2020	[394]
CO <sub>2</sub>	Carbonation	25/9.93	Aggregate	2017	[395]
CO <sub>2</sub>	Carbonation	105/0.1	Aggregate	2021	[396]
CO <sub>2</sub>	Carbonation	25/0.1–5	Concrete aggregates	2017	[397]
CO <sub>2</sub>	Carbonation	20 – 80/10 – 60	–	2017	[398]
CO <sub>2</sub>	Carbonation	20/1	–	2018	[399]
CO <sub>2</sub>	Carbonation	25/1	–	2017	[400]
CO <sub>2</sub>	Carbonation	50/10	–	2016	[401]

heterogeneous catalysts for direct carbon dioxide conversion to syngas.<sup>525</sup> Heterogeneous catalysis powered by sunlight has proven to be a viable and economical approach for converting CO<sub>2</sub> to methane.<sup>525</sup>

Several new metal catalysts and production techniques known as the Sabatier reaction have been discovered. Studies revealed

that Ru was the most active catalyst at the time.<sup>526</sup> Thermodynamics dictates that moderate temperatures ( $T \leq 300$  °C,  $P \leq 10$  bar) are required to obtain the desired quality without needlessly increasing pressure. In such cases, the design of the catalyst is crucial for overcoming kinetic constraints, achieving adequate reaction rates, and minimizing reactor volumes.

**Table 16.** Studies on CO<sub>2</sub> to syngas.

FEED	Process	Operating conditions (°C/bar)	Catalyst	Publication year	Source
CO <sub>2</sub> , solar light and H <sub>2</sub> O	Photochemical	95/1	Au@Cr <sub>2</sub> O <sub>3</sub>	2022	[404]
CO <sub>2</sub>	Photochemical	20/1	Polyoxometalates/Rull Composite	2020	[405]
CO <sub>2</sub> and N	Photochemical	25/1	TEOA and COF1-g-C <sub>3</sub> N <sub>4</sub>	2022	[406]
CO <sub>2</sub>	Photochemical	25/1	Ni-Co <sub>3</sub> O <sub>4</sub> NSDHN	2022	[407]
CO <sub>2</sub>	Photochemical	25/1	Co-TBAPy	2022	[408]
CO <sub>2</sub>	Photochemical	25/1	Hexanuclear cobalt metal-organic	2017	[409]
CO <sub>2</sub>	Photochemical	25/1	(Co/Ru)-UiO67(bpydc)	2019	[410]
CO <sub>2</sub>	Photochemical	25/1	CdSNRs/Fe(III)Salen	2020	[411]
CO <sub>2</sub> and H <sub>2</sub> O	Photochemical	25/1	CoII(Ch)	2016	[412]
CO <sub>2</sub>	Photochemical	25/1	[Co <sub>5</sub> (btz) <sub>6</sub> (NO <sub>3</sub> ) <sub>4</sub> (H <sub>2</sub> O) <sub>4</sub> ]	2022	[413]
CO <sub>2</sub>	Photochemical	80/1	LDH	2021	[414]
CO <sub>2</sub>	Photochemical	80/1	LDH/TiC (1.7–1.0)	2021	[414]
CO <sub>2</sub>	Photochemical	80/1	TiC	2021	[414]
CO <sub>2</sub>	Photochemical	80/1	LDH/TiC	2021	[414]
CO <sub>2</sub>	Photochemical	80/1	LDH/TiC-1.2	2021	[414]
CO <sub>2</sub>	Photochemical	25/1	LDHs, Ce-x	2021	[415]
CO <sub>2</sub> and H <sub>2</sub> O	Photochemical	25/1	Pd/layered double hydroxide nanosheets	2019	[416]
CO <sub>2</sub>	Photochemical	120/1	Fe/Ni MOFs	2020	[417]
CO <sub>2</sub>	Photochemical	25/1	Fe-SAs/N-C	2020	[418]
CO <sub>2</sub> and H <sub>2</sub> O	Photochemical	25/1	Cobalt bipyridyl complex	2018	[419]
CO <sub>2</sub> and H <sub>2</sub> O	Photochemical	25/1	MnOx and CuPt	2018	[420]

**Table 16.** (continued)

FEED	Process	Operating conditions (°C/bar)	Catalyst	Publication year	Source
CO <sub>2</sub> and H <sub>2</sub> O	Photochemical	25/1	Rh-Au@STO	2016	[421]
CO <sub>2</sub>	Photochemical	25/1	BP/monolayer Bi <sub>2</sub> WO <sub>6</sub>	2021	[422]
CO <sub>2</sub>	Photochemical	25/1	CoFeO <sub>x</sub> nanosheets	2022	[423]
CO <sub>2</sub>	Photochemical	25/1	H <sub>2</sub> Ti <sub>6</sub> O <sub>13</sub>	2021	[424]
CO <sub>2</sub>	Photochemical	25/1	POM-incorporated CoO UNWs	2020	[425]
CO <sub>2</sub>	Photochemical	25/1	ZnIn <sub>2</sub> S <sub>4</sub> nanosheets	2020	[426]
CO <sub>2</sub>	Photochemical	25/1	M–N–C	2020	[427]
CO <sub>2</sub>	Electrochemical	25/1	Palladium-based	2020	[428]
CO <sub>2</sub>	Photochemical	25/1	Transition metal nitrides	2020	[429]
CO <sub>2</sub>	Photochemical	25/1	Co and Ni single-atom	2020	[430]
CO <sub>2</sub>	Photochemical	25/1	Cobalt–carbon composite	2020	[431]
CO <sub>2</sub>	Electrochemical	25/1	Cu/In <sub>2</sub> O <sub>3</sub>	2018	[432]
CO <sub>2</sub>	Photochemical	25/1	Amorphization-activated copper indium core–shell	2022	[433]
CO <sub>2</sub>	Electrochemical	25/1	–	2017	[434]
CO <sub>2</sub>	Photochemical	550/20	–	2020	[435]
CO <sub>2</sub>	Photochemical	25/1	40LaNi0.75Fe0.25O <sub>3</sub> /SiO <sub>2</sub>	2018	[436]
CO <sub>2</sub> and H <sub>2</sub> O	Thermochemical	560–700/1	Doped ceria-zirconia materials	2020	[437]
CO <sub>2</sub>	–	300–900/1–20	Ethanol and glycerol	2019	[438]
CO <sub>2</sub> and glycerol	Photochemical	100/1	Ag–Ni/SiO <sub>2</sub>	2016	[439]

Nickel is an affordable and readily available active material that can accomplish these reaction rates. On nickel catalysts, high values (> 99%) of selectivity are readily attained.<sup>527</sup> However,

enhancing low-temperature activity is challenging when utilizing Ni-based catalysts for carbon dioxide methanation since high-temperature reactions are constrained by chemical equilibrium

**Table 17.** Studies on CO<sub>2</sub> to fuels.

FEED	Catalyst	Operating conditions	Products	Publication year	Source
CO <sub>2</sub>	Fe–Mn–K	300/10	Jet fuel	2020	[440]
CO <sub>2</sub>	CuFeO <sub>2</sub>	300/10	Liquid fuels and olefins	2017	[441]
CO <sub>2</sub>	Fe–Co/K/Al <sub>2</sub> O <sub>3</sub>	300/11	Liquid fuels and olefins	2017	[441]
CO <sub>2</sub>	Na–Fe <sub>3</sub> O <sub>4</sub> /HZSM-5	320/30	High-density and high-value fuels	2019	[442]
CO <sub>2</sub>	FeNa	320/30	Light olefins	2016	[443]
CO <sub>2</sub> and H <sub>2</sub>	Na–Fe <sub>3</sub> O <sub>4</sub> /HMCM22	320/30	Isoparaffins	2018	[444]
CO <sub>2</sub> and H <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub> _CT600	350/15	C <sub>5+</sub> hydrocarbons	2017	[445]
CO <sub>2</sub> and H <sub>2</sub>	C <sub>06</sub> /MnO <sub>x</sub>	200/80	Liquid fuel	2019	[446]
CO <sub>2</sub> and H <sub>2</sub>	Fe–Zn–Zr@HZSM5–Hbeta	340/50	Isoalkanes	2016	[447]
CO <sub>2</sub>	AU-H	25/5	Fuel	2016	[448]
CO <sub>2</sub>	Palladium-gold	25/1	C <sub>1</sub> to C <sub>5</sub> hydrocarbons	2016	[449]
CO <sub>2</sub>	nickel phosphides	35/10	C <sub>3</sub> and C <sub>4</sub> oxyhydrocarbons	2018	[450]
CO <sub>2</sub>	Cu-containing metal	25/10	C <sub>2+</sub> hydrocarbons (oxygenates)	2018	[451]
CO <sub>2</sub>	Nanoporous Cu films	25/1	Ethylene or ethane	2016	[452]
CO <sub>2</sub>	Anodized Cu	25/1	Ethylene	2018	[453]
CO <sub>2</sub>	Copper nanoparticle	25/1	C <sub>2</sub> –C <sub>3</sub> products	2017	[454]
CO <sub>2</sub>	Nano dendritic copper	60/1	Ethylene	2017	[455]
CO <sub>2</sub>	Porous Cu	25/1	Ethene	2017	[456]
CO <sub>2</sub>	CuO-derived copper	25/1	C2 products	2017	[457]
CO <sub>2</sub>	Polycrystalline copper	25/1	C ≥ 2 Products	2017	[458]
CO <sub>2</sub>	3,5-Diamino-1,2,4-triazole (DAT)	25/1	Ethylene and ethanol	2018	[459]

**Table 17.** (continued)

FEED	Catalyst	Operating conditions	Products	Publication year	Source
CO <sub>2</sub>	Hydroxide-mediated copper	25/1	Ethylene	2018	[460]
CO <sub>2</sub> and H <sub>2</sub>	Ni/Al <sub>2</sub> O <sub>3</sub>	900/2.3	Fuels, methanol, and 1-propanol	2021	[461]
CO <sub>2</sub> and H <sub>2</sub>	Heterogeneous	Review	CH <sub>4</sub> , lower olefins, gasoline, or long-chain hydrocarbons	2018	[462]
CO <sub>2</sub> and H <sub>2</sub>	NiWMgOx	300/1	Methane	2016	[463]
CO <sub>2</sub> and H <sub>2</sub>	– (Thermochemical)	–/–	Methane	2018	[464]
CO <sub>2</sub> and H <sub>2</sub>	10Ni/Ce–ZrO <sub>2</sub>	275/1	Methane	2017	[465]
CO <sub>2</sub> and H <sub>2</sub>	Ni (electrochemical)	25/1	Methane	2021	[466]
CO <sub>2</sub> and H <sub>2</sub>	20% Ni/55% g-Al <sub>2</sub> O <sub>3</sub> –15% ZrO <sub>2</sub> –15% TiO <sub>2</sub> –15% CeO <sub>2</sub>	300/1	Methane	2016	[467]
CO <sub>2</sub> and H <sub>2</sub>	10% Ni/TiO <sub>2</sub>	350/1	Methane	2016	[468]
CO <sub>2</sub> and H <sub>2</sub>	One-pot tandem (electrochemical)	–/–	Methane	2019	[469]
CO <sub>2</sub> and H <sub>2</sub>	10Ni3Pr/Al <sub>2</sub> O <sub>3</sub>	400/1	Methane	2017	[470]
CO <sub>2</sub> and H <sub>2</sub>	Tw-Cu and Pc-Cu (electrochemical) Co–80% Al <sub>2</sub> O <sub>3</sub>	400/1	Methane	2016	[471]
CO <sub>2</sub> and H <sub>2</sub>	Solid basic oxides (photocatalytic)	25/1	Methane	2020	[472]
CO <sub>2</sub> and H <sub>2</sub>	Pt@CSN	320/30	Methane	2017	[473]
CO <sub>2</sub> and H <sub>2</sub>	Ag/In <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub> (photocatalytic)	50/2	Methane	2022	[474]
CO <sub>2</sub> and H <sub>2</sub>	2.5% Ru/P25	200/1	Methane	2016	[475]
CO <sub>2</sub> and H <sub>2</sub>	Ru/CeO <sub>2</sub>	300/1	Methane	2017	[476]
CO <sub>2</sub> and H <sub>2</sub>	20% Fe/cube-CeO <sub>2</sub>	390/1	C <sub>2+</sub> hydrocarbons	2016	[477]
CO <sub>2</sub> and H <sub>2</sub>	10K13Fe2Co100ZrO <sub>2</sub>	400/30	C <sub>2+</sub> hydrocarbons	2018	[478]

Table 17. (continued)

FEED	Catalyst	Operating conditions	Products	Publication year	Source
CO <sub>2</sub> and H <sub>2</sub>	CeO <sub>2</sub> -Pt@mSiO <sub>2</sub> -Co	250/6	C <sub>2+</sub> hydrocarbons	2017	[479]
CO <sub>2</sub> and H <sub>2</sub>	0.05MnFe	340/1	C <sub>2+</sub> hydrocarbons	2018	[480]
CO <sub>2</sub> and H <sub>2</sub>	ZnZrO/SAPO-34	320/20	C <sub>2+</sub> hydrocarbons	2017	[481]
CO <sub>2</sub> and H <sub>2</sub>	In <sub>2</sub> O <sub>3</sub> /HZSM-5	340/30	C <sub>2+</sub> hydrocarbons	2017	[482]
CO <sub>2</sub> and H <sub>2</sub>	In-Zr/SAPO-34	400/30	C <sub>2+</sub> hydrocarbons	2017	[483]
CO <sub>2</sub> and H <sub>2</sub>	Na-Fe <sub>3</sub> O <sub>4</sub> /HZSM-5	320/30	C <sub>2+</sub> hydrocarbons	2017	[484]

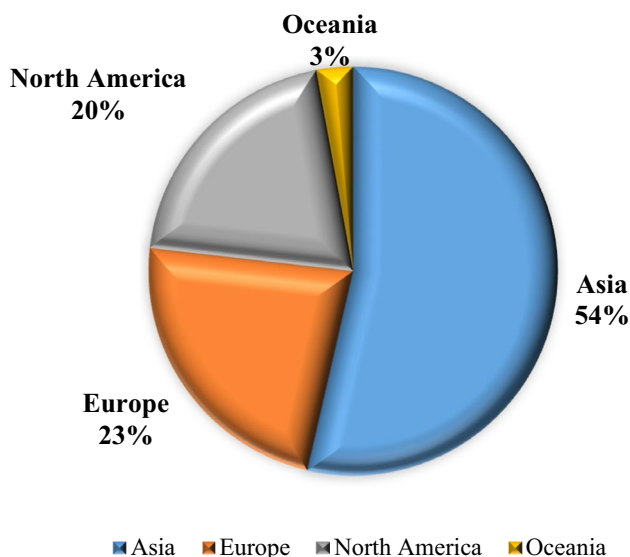


Figure 7. Global distribution of CO<sub>2</sub> conversion facilities.

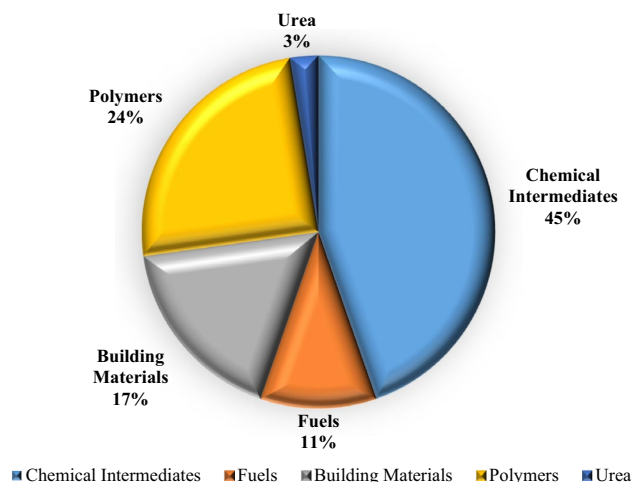


Figure 9. Percentage share of published articles.

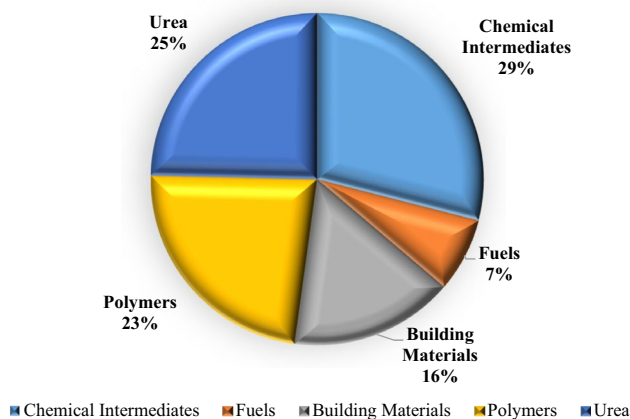


Figure 8. Global CO<sub>2</sub> conversion facilities based on products.

and energy conservation. Due to their excellent thermal stability and low cost, traditional metal oxides continue to be the most promising support for optimizing Ni-based catalysts for carbon dioxide methanation.<sup>466</sup> Ni exhibits strong action toward methane and excellent selectivity. However, as heat evolves from the extremely exothermic methanation reaction, conventional Ni-catalysts experience deactivation due to the sintering of the Ni particles. Further catalyst degradation is caused by coke deposition and the production of volatile nickel carbonyles. Additionally, Ni raises toxicological concerns. On the other hand, Fe has poor selectivity but a very high activity for CO<sub>2</sub> activation. Fe is 180 times less expensive than nickel since it is far more abundant and nontoxic than nickel.<sup>529</sup> Besides Ni, there are other metals that are active in methane production via carbon dioxide. These metals for methane catalysts are based on their activity (Ru > Fe > Ni > Co) and selectivity to methane (Ni > Co > Fe > Ru).<sup>529</sup>

**Table 18.** Characteristics of the various methods of CO<sub>2</sub> conversion.

Method	Products	Advantages	Disadvantages
Photochemical	FA and methane, <sup>492</sup> urea syngas, urea	Eco friendly Cost-effective Energy consumption is less	Product and catalyst separation is difficult Low product yield Low product selectivity
Electrochemical	Formic acid, methanol, fuel, <sup>9,492,494</sup> urea	Scale-up is easy Additional heat is not required	Catalyst life span is low High OPEX Require high electrical energy
Thermal	Methane, methanol, <sup>9,493</sup>	High Yield	High-temperature requirements
Chemical	Urea, DME, methanol <sup>9</sup>	CO <sub>2</sub> is used as raw materials	High cost

### Future perspective

Carbon dioxide utilization is a possible way of reducing the cost of the CCS value chain. Converting the captured and stored carbon dioxide into value-added products could reduce the costs of building new CCS facilities or retrofitting existing ones. This process is known as integrated carbon capture storage and utilization (CCSU). The utilization pathway of carbon dioxide could be economically sound, and its usage is increasing drastically worldwide in various sectors: chemical, fuel, agriculture, and mineralization through direct or indirect processes. However, the research analysis showed that the successful conversion of CO<sub>2</sub> to value-added products depends on the type of catalyst, hydrogen availability, energy requirements, and economics, among other factors. This implies that the energy requirements, the type of catalyst used, and the sources of hydrogen production could go a long way in determining the process's cost-effectiveness, yield, efficiency, and sustainability.

The literature analysis showed that synthesizing chemical intermediate products like methanol DME and polymers often occurs at high temperatures and pressures, except in the study of Gonzalez-Garay et al.,<sup>79</sup> which produced methanol at low temperatures (25 °C) and pressures (1 bar). The increased cost is one significant implication of producing these materials from CO<sub>2</sub> at high temperatures and pressures. Reducing the energy requirements will help drive down the associated costs of the process, thereby making a good economic case for the CCSU process. Consequently, more research on reducing the energy requirements while improving the yields for chemical intermediates and polymer synthesis from CO<sub>2</sub> should be investigated. Furthermore, more emphasis should be placed on Gonzalez-Garay et al.<sup>79</sup>'s work on methanol synthesis, where they simulated methanol production at near atmospheric conditions of 25 °C and 1 bar. Their work should be further investigated to see how the energy requirements of methanol and, by extension, DME and polymers could be reduced.

The development of competitive catalytic technologies for the selective catalytic hydrogenation and other carbon dioxide conversion processes to products offers a path forward to reducing the enormous carbon dioxide emissions from fossil fuels by converting them to valuable materials and products. Catalysis and catalyst development is a growing research interest in converting CO<sub>2</sub> to fuels and chemical products. However, there is still no preferable approach and a better class of efficient catalysts for converting CO<sub>2</sub> to fuels and chemicals in terms of cost-efficiency and optimum production.<sup>530</sup> From the analysis of the published literature, most of the catalyst used in the conversions are inefficient and requires some reducing agents/metal-based materials. It is anticipated that cost-effective, efficient, and sustainable catalyst development represents a challenging problem in the different CO<sub>2</sub> to chemical/fuel synthesis. Therefore, researchers should focus on developing efficient and cost-effective catalysts for CO<sub>2</sub> conversion processes.

Hydrogen is vital to the CO<sub>2</sub> hydrogenation process, syngas synthesis, and urea production. A cleaner, cost-effective, and efficient technology for hydrogen production will go a long way in enhancing a sustainable CO<sub>2</sub> conversion process. Various categories of hydrogen production techniques, including the conventional hydrogen production process from fossil fuels, thermolysis, solar energy processes, water electrolysis, and other novel methods, can be further researched to find a reliable, suitable, sustainable, and cost-effective way of hydrogen production required for an efficient CO<sub>2</sub> conversion process. Researchers should optimize proper hydrogen production techniques to make the CCS process economically viable.

Calcium carbonate (CaCO<sub>3</sub>) can be used in many applications, including building materials. The conversion of CO<sub>2</sub> to CaCO<sub>3</sub> can help protect the depleting limestone (natural) resources. Published works on this subject have shown the possibility of converting CO<sub>2</sub> to calcium carbonate (CaCO<sub>3</sub>). In one such study, CO<sub>2</sub> was converted to CaCO<sub>3</sub> when passed through a Nickel catalyst.<sup>531</sup> In another study, CO<sub>2</sub> was converted to CaCO<sub>3</sub> using genetically altered yeast.<sup>532</sup> Other studies on CO<sub>2</sub>

conversion to  $\text{CaCO}_3$  used the amine looping strategy,<sup>533</sup> membrane gas absorption,<sup>530</sup> and ultrasonic carbonization.<sup>534</sup> The application of  $\text{CO}_2$  in construction materials is gaining traction. Even if the industrial trials mentioned in the above research publications demonstrate that  $\text{CO}_2$  may be employed in construction components, scalability and market viability are still impacted by a variety of factors. Some challenges in the production of building materials via  $\text{CO}_2$  usually include the unavailability of raw materials, the cost of carbonated products, and the distance of  $\text{CO}_2$  source and suitability. Others are carbonation reaction and processing and the construction codes and standards. It is challenging to commercialize these items on a broad scale due to the lack of strict adherence to construction standards and rules. Another issue is that construction codes frequently describe the materials' composition rather than the performance criteria, making them more prescriptive than performance-based. In the short to medium term, there is a tremendous opportunity for  $\text{CO}_2$  usage in the market for construction materials. Although several chemical and biological use approaches are more advanced in process technology than carbonation-based concrete curing, additional study is needed to address significant issues with carbonation technology, processing, and market adoption. Breakthrough studies on the transformation of  $\text{CO}_2$  to  $\text{CaCO}_3$  can proffer a profitable pathway for the carbon capture process and should, therefore, be investigated.

The study showed that most of the existing conversion facilities and published research articles in recent times focused more on  $\text{CO}_2$  conversion to chemical intermediates, polymers, and building materials. This suggests that converting  $\text{CO}_2$  to these products could be critical to CCUS's economic viability. It also indicates the viability of the chemical intermediates, polymers, and building materials markets. Consequently, more studies should be conducted to create energy-efficient processes and technologies for improving and optimizing  $\text{CO}_2$  conversion to chemical intermediates, polymers, and building materials. Furthermore, facilities for converting  $\text{CO}_2$  to fuels are the least globally. Also, the research publications on fuel production from  $\text{CO}_2$  are relatively low. Having been identified as one of the potentially viable and promising materials derivable from  $\text{CO}_2$ ,<sup>16</sup> fuel synthesis from  $\text{CO}_2$  can become a reliable decarbonization strategy for the transport sector, especially the aviation and maritime industries. These transport industry sectors will continue to play a vital role in globalization and trade and are expected to grow significantly as the global population increases. The aviation and maritime industries currently contribute significant GHG emissions, resulting in global warming and severe environmental consequences. Hence, utilizing gaseous or liquid fuels in both sectors can help achieve net-zero targets and carbon neutrality in critical transport industry sectors.

Consequently, more studies are required in  $\text{CO}_2$  conversion to aviation and maritime fuels to decarbonize the sectors and gain more insights into  $\text{CO}_2$  conversion to fuels. Furthermore, the importance of urea fertilizer in crop production and food and energy security cannot be over-emphasized. Hence, further investigations are needed to expand the frontiers of  $\text{CO}_2$  conversion to these products.

## Conclusion

Carbon dioxide utilization offers a pathway for reducing the costs of the CCS process, producing carbon-neutral products, and endearing a sustainable environment. This review has analyzed the existing global  $\text{CO}_2$  utilization facilities based on location and product type. Furthermore, published articles on  $\text{CO}_2$  conversion to materials identified in the  $\text{CO}_2\text{U}^{16}$  report as viable priorities for  $\text{CO}_2$  utilization were also analyzed. The analysis of the conversion facilities was done based on a 90% confidence limit within a 9.93% margin of error. Likewise, the study on the published articles was done based on a 95% confidence limit within a 5% margin of error. The following conclusions can be drawn from the study.

1. Over 90% of global  $\text{CO}_2$  conversion facilities produce chemical intermediates, urea, polymers, and building materials, and less than 10% produce fuels.
2. More than half of the global  $\text{CO}_2$  conversion facilities are in South-East Asia (mainly China), with the remaining in Western Europe (23%), North America (20%), and Oceania (3%). Developing countries in Africa, Central and South America, and others are far behind in the CCUS process as there are currently too few or no  $\text{CO}_2$  conversion facilities in those regions. This is a call for concern with respect to the global clean energy initiative.
3. The analysis of the research publications from 2016 to 2022 shows that the research focus is currently on  $\text{CO}_2$  conversion to chemical intermediates, polymers, building materials, and fuels (over 95%) and less on urea.
4. A future perspective on  $\text{CO}_2$  conversion includes increasing research output and conversion facilities on fuels to specifically help decarbonize the aviation and maritime sectors while adopting energy-efficient processes and technologies for cost-effective and efficient  $\text{CO}_2$  conversion.

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## Author contributions

All the authors contributed to the final version of this manuscript. Adeyemi, MA, did the formal analysis and wrote the first draft. Aimikhe, VJ reviewed and edited the first and final manuscript drafts and did research conceptualization, theoretical framework, and supervision.

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The authors have no relevant financial or non-financial interests to disclose.

### Ethical approval

Not applicable.

### Consent to participate

Not applicable.

### Consent for publication

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