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Showcasing the technological advancements of carbon dioxide conversion: a pathway to a sustainable future

Xiao Jiang

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Introduction

The global reliance on fossil fuels has driven an unprecedented increase in atmospheric carbon dioxide (CO_2) concentrations (425 ppm as of December 2024),[1] resulting in climate change, ocean acidification, and ecosystem disruptions. While renewable energy solutions, such as solar and wind power, provide avenues to decarbonization, they alone are insufficient to address all challenges pertaining to CO_2-emission issues. Therefore, CO_2 conversion represents a crucial strategy to transform this greenhouse gas into valuable chemicals, fuels, and materials. Extending far beyond climate mitigation, CO_2 conversion also offers the possibility of revolutionizing industries and creating sustainable economies.

The world of industry has taken accountable actions to seek solutions to decarbonization, and most of them have committed to achieving net-zero emissions by 2050 with pragmatic strategies and trackable annual reports, such as the oil and gas industry (*e.g.*, Aramco, ExxonMobil, Chevron, Shell, *etc.*)[2–5] and chemical/materials producers (*e.g.*, Dow , Cabot, *etc.*).[6,7] Together with academia (*e.g.*, Global CO_2 Initiative, University of Michigan, *etc.*),[8] startups (*e.g.*, Carbon Utilization Alliance, *etc.*),[9] and government-supported institutes/laboratories, these are major contributors that are advancing technological frontiers toward decarbonization.

In recent years, there have been advancements in CO_2-conversion technologies, and products range from synthetic fuels to bioplastics. Researchers have made significant endeavors in understanding the mechanisms of CO_2 activation and conversion, the development of novel catalysts, the exploration of a wide array of approaches, as well as the development of process and techno-enviro-economic models that could broaden the potential for large-scale implementations. Among all research approaches, thermocatalysis is prevailing. In general, the source of hydrogen determines the major reaction paths of CO_2 conversion. For example, direct hydrogenation uses H_2, while CO_2-assisted oxidative light alkane to alkenes conversion uses the abstracted hydrogen from alkane molecules during the reaction. Given the respective achievements in capture and conversion, efforts in integrating these two processes are underway and target a more energy-efficient process to reduce the carbon intensity. Meanwhile, people are paying more attention to disruptive approaches to convert CO_2, such as electrochemical, photochemical, plasmachemical, mechanochemical, and enzymatic approaches.[10] Hybridizing with the existing thermocatalytic technologies, these disruptive approaches not only facilitate CO_2 activation and overcome the thermodynamic limitations, but they also potentially provide avenues to net-zero carbon emissions with the assistance of deployed renewable-energy technologies.[11] In parallel, biotechnological approaches are being explored as a more sustainable, cost-effective solution, which leverage natural processes to reduce CO_2 into useful compounds, potentially providing an alternative to energy-intensive chemical processes.

The research featured in this collection represents diverse approaches, innovative solutions, and visionary perspectives in the scope of CO_2 conversion. From advances in catalyst design to breakthroughs in microbial systems, this collection is showcasing the exciting developments in a variety of approaches (thermochemical and photochemical approaches, mineralization, enzymatic carboxylation, *etc.*) for efficient CO_2 conversion to value-added products including single carbon products (*e.g.*, carbon monoxide, formic acid, methane, methanol, *etc.*) and multi-carbon products (*e.g.*, hydrocarbons, alcohols, acetic acid, polymers, *etc.*).

• As aforementioned, the thermochemical approach is the prevailing approach for CO_2 conversion, and major efforts are devoted to developing catalysts

Aramco Americas – Boston Downstream Research Center, 400 Technology Square, Cambridge, MA 02139, USA

with desired features to manipulate the reaction pathways in favor of targeted products. Cleaving C–O bond(s) in the presence of H_2 or hydrocarbon-provided H species has been widely applied to activate and convert CO_2 molecules under harsh conditions (*e.g.*, high pressures and temperatures). Reactions that researchers/scientists are pursuing include dry reforming of light alkanes in the presence of CO_2, reverse water–gas shift (RWGS), CO_2-assisted light alkane dehydrogenation to alkenes, and CO_2 hydrogenation to oxygenates and hydrocarbons. In addition to the inertness of CO_2 molecules, thermodynamic limitations, the high energy barrier of carbon–carbon coupling, and coke- and/or sintering-induced rapid catalyst deactivation are major hurdles that impair efforts in implementing these technologies for practical use. In this collection, developed catalysts for advancing thermocatalytic CO_2-conversion technologies include traditional supported copper–palladium nanoparticles (NPs) (https://doi.org/10.1039/D4SU00339J), supported Ru catalyst (https://doi.org/10.1039/D4SU00469H), supported vanadia catalysts (https://doi.org/10.1039/D4SU00527A), perovskite-based catalysts (*e.g.*, https://doi.org/10.1039/D4SU00410H), and zirconium-based solid-solution catalysts (*e.g.*, https://doi.org/10.1039/D4SU00522H).

Converting CO_2 to carbons is also promising, as it provides alternatives to meet the market demand for carbon products while meeting a net-zero future. The present collection includes a contribution on developing a barium titanate nanocatalyst (https://doi.org/10.1039/D4SU00253A) for this field. Meanwhile, there are also advancements in converting CO_2 by maintaining both C–O bonds with improved atomic efficiency, and representative products include formic acid, acetic acid, and methyl formate. In selectively produce these products, the inert nature of CO_2 molecules and the requirement of mild reaction conditions render the catalyst development particularly challenging. Advancements in this field are covered in the present collection, such as xantphos macroligand (https://doi.org/10.1039/D4SU00164H), hydroxyapatite (https://doi.org/10.1039/D4SU00305E), and Cu–Mg catalysts (https://doi.org/10.1039/D4SU00478G).

• As a complementary field of thermocatalysis, the integrated capture and conversion of CO_2 aims to improve energy efficiency. Contributions in the present collection not only include a prevailing approach of CO_2 capture and methanation *via* metal carbonates (https://doi.org/10.1039/D4SU00306C), but also a disruptive approach of the formic acid production through the reaction between captured CO_2 and biomass wastes (https://doi.org/10.1039/D4SU00440J).

• In addition to the above extensively studied areas, the present collection will also present examples of alternative CO_2-conversion approaches such as mineralization (https://doi.org/10.1039/D4SU00443D) and mechanochemical polymerization (https://doi.org/10.1039/D4SU00426D).

• Pursuing energy-effective approaches to convert CO_2 requires coordinated efforts and collaborations across sectors, in which process design plays an indispensable role. The present collection has a contribution from the area of process simulation, in which the authors studied the mass and heat transport behavior of a CO_2-conversion-relevant model reaction, syngas to dimethyl ether, and provided insights into the design of the reactor system and catalyst bed (https://doi.org/10.1039/D4SU00602J).

• Last but not least, this collection includes critical review articles overviewing three popular CO_2-conversion research areas, namely CO_2 methanation through single-atom catalysis (SAC) (https://doi.org/10.1039/D4SU00069B), CO_2 sequestration through various approaches (https://doi.org/10.1039/D4SU00482E), and CO_2 hydrogenation to higher alcohols (https://doi.org/10.1039/D4SU00497C). This collection also presents a unique perspective that conveys the contributors' own experience in advancing biocatalytic CO_2 valorization, offering constructive criticism and practical advice to manage an efficient CO_2-conversion-based consortium from the managerial point of view (https://doi.org/10.1039/D4SU00274A).

Concluding remarks

CO_2 conversion provides a pathway that offers both environmental benefits and economic opportunities. Integrating CO_2-conversion technologies into existing industries while maintaining economic competitiveness with their fossil-based counterparts will require robust collaborations between academia, industry, and governments to align technical, economic, and environmental goals. This collection showcases the recent technological advancements in turning CO_2 into value-added products, helping to pave the way toward a sustainable, low-carbon future.

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