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Chemistry of carbon capture and CO_2 conversion to fuels

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ABSTRACT

This paper critically examines the chemistry underlying various carbon capture technologies—including amine-based solvents, solid sorbents, mineralization, and electrochemical methods—and explores their potential for sustainable energy through the conversion of captured CO_2 into fuels. Carbon capture techniques, essential to mitigating rising atmospheric CO_2 levels, rely fundamentally on chemical interactions that enable effective sequestration and subsequent utilization. Amine-based solvent capture operates through reversible acid-base reactions, with amines binding CO_2 as carbamates, allowing efficient regeneration and high purity CO_2 streams suitable for downstream applications. Solid sorbents, which include activated carbons, zeolites, and metal-organic frameworks (MOFs), offer alternative CO_2 capture routes via physisorption or chemisorption mechanisms. Advances in solid sorbents focus on enhancing stability, capacity, and selectivity, particularly for direct air capture applications. Mineralization processes capitalize on the reaction between CO_2 and basic metal oxides or silicates, converting CO_2 into thermodynamically stable carbonate minerals, providing a robust, long-term carbon sequestration pathway. Meanwhile, electrochemical methods employ electricity-driven reactions, such as pH swings and electro-swing adsorption, to capture CO_2 under milder, renewable-powered conditions, potentially enhancing energy efficiency and scalability. Captured CO_2 can subsequently serve as a valuable feedstock for producing fuels such as methanol, methane, and syngas. The catalytic hydrogenation of CO_2 into methanol and methane involves complex reaction networks and equilibrium considerations, heavily dependent on catalytic materials and process conditions. Syngas production, via the reverse water-gas shift reaction or co-electrolysis in solid oxide electrolysers, further exemplifies the integration of capture and conversion technologies. The paper also addresses challenges inherent to these technologies, including energy intensity, material stability, reaction selectivity, and scalability. Current research innovations, including advanced sorbents, electrochemical regeneration methods, and integrated capture-conversion systems, are highlighted as promising solutions to overcome these barriers. Finally, this research underscores the critical role of carbon capture and utilization technologies in achieving sustainable energy systems, facilitating the production of carbon-neutral or negative-emission fuels essential for mitigating climate change and transitioning to a circular carbon economy.

KEY WORDS

Carbon capture technologies, CO_2 conversion, sustainable fuels, amine-based solvents, solid sorbents, mineralization, electrochemical capture, catalytic hydrogenation, syngas production, carbon-neutral energy, circular carbon economy, climate change mitigation.

BIOGRAPHY

Mr Navdeep Singh Gill is pursuing his PhD at the Australian Maritime College (AMC), University of Tasmania (UTAS), focusing on the decarbonisation of Australian ports. He holds two MBA degrees from UTAS, reflecting his robust academic foundation. Prior to his academic career, Mr Gill served as a Class 2 Engineer in the Merchant Navy, gaining extensive maritime experience. His research investigates strategic approaches, emerging technologies, and policy frameworks necessary for Australian ports to achieve net-zero emissions by 2050. Mr Singh actively engages with industry stakeholders, policymakers, and researchers, contributing significantly to sustainable maritime operations and environmental responsibility.

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