

DOI: 10.36297/vw.jei.v8i2.401

VW Engineering International, Volume: 8, Issue: 2, 01-04

Carbon Capture and Utilization Technologies for Industrial Emission Reduction and Circular Economy

Arun Mehta^{1*}, Ritika Sharma^{2*}, Imran Hossain^{3*}

¹Department of Civil Engineering, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal, India

²Department of Materials Engineering, Sant Longwal Institute of Engineering and Technology, Punjab, India

³Department of Environmental Engineering, Shahjalal University of Science and Technology, Sylhet, Bangladesh

*Email: arun.m@rgpv.ac.in, ritikashar.ma@sliet.ac.in, imran.h@sju.ac.bd

Received:
Jan 04, 2026
Accepted:
Apr 06, 2026
Published online:
Apr 06, 2026

Abstract: Industrial carbon dioxide emissions are a major contributor to global climate change, necessitating the development of advanced mitigation strategies that align with sustainable development goals. Carbon capture and utilization technologies have emerged as promising approaches for reducing greenhouse gas emissions while enabling the conversion of captured carbon into value-added products. This study presents a comprehensive analysis of carbon capture methods, including post-combustion, pre-combustion, and oxy-fuel combustion, along with emerging utilization pathways such as chemical synthesis, mineralization, and bio-conversion. The research evaluates the efficiency, cost, and environmental impact of various technologies, integrating process modeling and life cycle assessment to determine their feasibility. The findings indicate that advanced solvents, solid sorbents, and membrane-based systems significantly improve capture efficiency, while utilization pathways contribute to the development of a circular carbon economy. The study highlights the potential of integrating carbon capture and utilization systems into industrial processes to reduce emissions, enhance resource efficiency, and support sustainable industrial growth.

Keywords: Carbon Capture, Utilization, Industrial Emissions, Circular Economy, Sustainable Engineering

1. Introduction

The rapid industrialization of the global economy has led to a significant increase in greenhouse gas emissions, particularly carbon dioxide, which is a primary driver of climate change. Industrial sectors such as power generation, cement production, and chemical manufacturing contribute substantially to global emissions, necessitating the development of effective mitigation strategies [1]. Traditional approaches to emission reduction, including energy efficiency improvements and renewable energy adoption, are essential but insufficient to meet global climate targets. Carbon capture and utilization has emerged as a promising solution that not only reduces emissions but also transforms carbon dioxide into valuable products. Unlike carbon capture and storage, which focuses on long-term sequestration, CCU emphasizes the reuse of captured carbon in industrial processes, thereby contributing to a circular economy [2]. This approach aligns with sustainability goals by reducing waste and promoting resource efficiency.

2. Carbon Emissions and Industrial Impact

Industrial processes release carbon dioxide through combustion of fossil fuels and chemical reactions. For example, cement production involves the decomposition of limestone, which releases CO₂ as a byproduct. Similarly, steel manufacturing and petrochemical processes generate significant emissions [3].

The accumulation of CO₂ in the atmosphere has led to global warming, ocean acidification, and other environmental impacts. Addressing these challenges requires the implementation of technologies capable of capturing and utilizing carbon emissions at the source.

3. Literature Review

Carbon capture technologies have been extensively studied, with various methods developed to improve efficiency and reduce costs. Post-combustion capture, which involves the removal of CO₂ from flue gases, is widely used due to its compatibility with existing infrastructure [4]. Pre-combustion capture, on the other hand, involves the conversion of fuel into a mixture of hydrogen and CO₂ before combustion, enabling easier separation.

Oxy-fuel combustion is another approach in which fuel is burned in pure oxygen, producing a concentrated stream of CO₂ that can be easily captured [5]. Advances in materials science have led to the development of improved solvents, solid sorbents, and membranes for carbon capture.

Utilization pathways for captured carbon include chemical synthesis, where CO₂ is converted into fuels and chemicals, and mineralization, which involves the reaction of CO₂ with minerals to form stable carbonates [6]. Biological approaches, such as algae cultivation, have also been explored for carbon utilization.

4. Carbon Capture Technologies

Carbon capture technologies can be broadly classified into three categories: post-combustion, pre-combustion, and oxy-fuel combustion. Post-combustion capture is the most widely implemented method, involving the use of chemical solvents to absorb CO₂ from flue gases. Advanced amine-based solvents have been developed to improve capture efficiency and reduce energy consumption [4].

Pre-combustion capture involves the gasification of fuel to produce synthesis gas, which is then processed to separate CO₂. This method is particularly suitable for integrated gasification combined cycle power plants. Oxy-fuel combustion produces a high-purity CO₂ stream, simplifying the capture process [5].

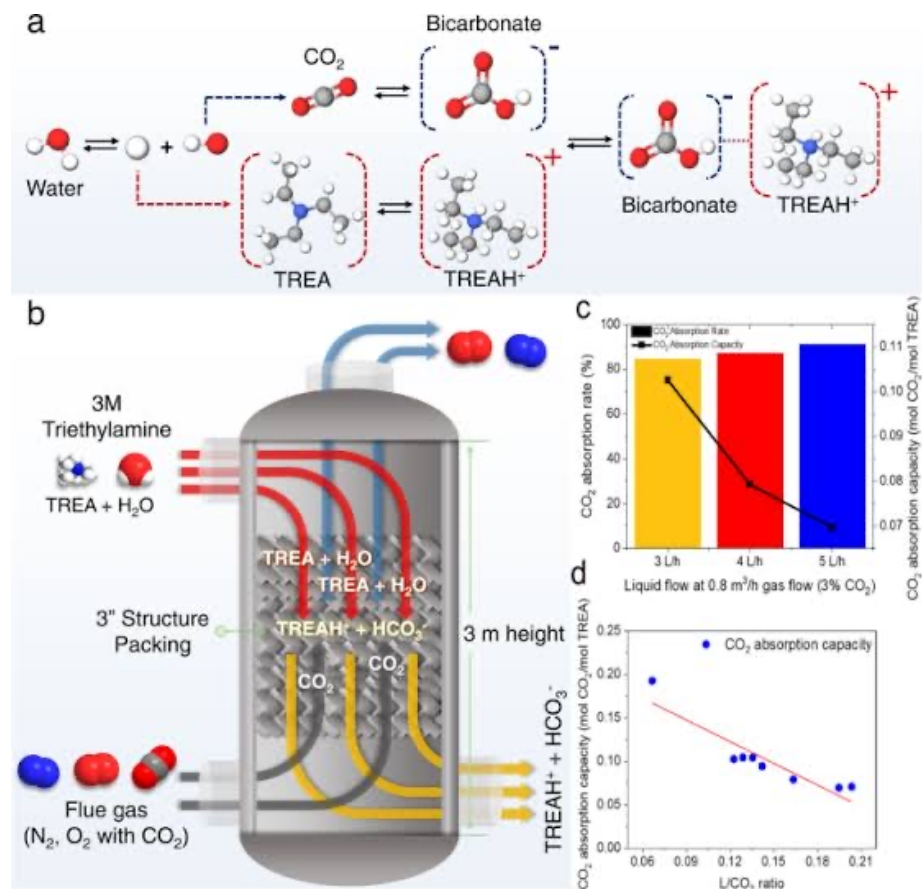


Fig. 1

5. Carbon Utilization Pathways

Captured CO₂ can be utilized in various applications, including the production of synthetic fuels, chemicals, and building materials. Chemical conversion processes, such as hydrogenation, can transform CO₂ into methanol and other valuable products [6]. Mineralization processes convert CO₂ into stable carbonates, which can be used in construction.

Biological utilization involves the use of microorganisms or algae to convert CO₂ into biomass and biofuels. These approaches offer sustainable alternatives for carbon utilization and contribute to the development of a circular carbon economy.

6. Methodology

The study employs process modeling and life cycle assessment to evaluate the performance of carbon capture and utilization technologies. Simulation tools are used to model capture processes and analyze their efficiency and cost. Life cycle assessment is conducted to evaluate environmental impacts, including energy consumption and emissions.

Data from industrial case studies and experimental research are used to validate the models and assess real-world applicability.

7. Results and Analysis

The results indicate that advanced carbon capture technologies can achieve capture efficiencies of over 90%, significantly reducing industrial emissions [4]. Membrane-based systems and solid sorbents demonstrate lower energy requirements compared to traditional solvent-based methods.

Utilization pathways contribute to the production of valuable products, offsetting the costs of carbon capture. Life cycle assessment shows that integrated CCU systems can reduce overall emissions and improve sustainability [6].

8. Discussion

The integration of carbon capture and utilization technologies into industrial processes offers significant potential for emission reduction and resource efficiency. By converting CO₂ into valuable products, CCU systems support the transition toward a circular economy.

However, challenges such as high capital costs, energy requirements, and scalability must be addressed. Policy support and technological innovation are essential for overcoming these barriers and promoting widespread adoption.

9. Industrial and Environmental Implications

The adoption of CCU technologies can significantly reduce the environmental impact of industrial activities. It also creates economic opportunities by generating value-added products from waste emissions.

The integration of CCU systems into existing industrial infrastructure can enhance sustainability and support global climate goals.

10. Future Scope

Future research should focus on developing cost-effective and energy-efficient capture technologies. Advances in materials science and process engineering can further improve system performance. Additionally, the integration of renewable energy sources can enhance the sustainability of CCU systems.

11. Conclusion

This study highlights the potential of carbon capture and utilization technologies in reducing industrial emissions and promoting a circular economy. The findings demonstrate that advanced capture methods and utilization pathways can significantly improve sustainability and resource efficiency. Continued research and innovation are essential for achieving large-scale implementation and addressing global climate challenges.

References

1. IPCC, "Climate Change Report," 2021.

2. S. Chu et al., “Carbon capture and utilization,” *Nature*, vol. 488, pp. 294–303, 2012.
3. International Energy Agency, “CO₂ Emissions Report,” 2020.
4. G. Rochelle, “Amine scrubbing,” *Science*, vol. 325, pp. 1652–1654, 2009.
5. J. Davison, “Oxy-fuel combustion,” *Energy*, vol. 32, pp. 1163–1176, 2007.
6. M. Aresta et al., “Utilization of CO₂,” *Chemical Reviews*, vol. 114, pp. 1709–1742, 2014.
7. D. Aaron and C. Tsouris, “Separation technologies,” *Separation Science*, vol. 40, pp. 321–348, 2005.
8. P. Styring et al., “Carbon capture roadmap,” 2011.
9. K. Sumida et al., “Carbon capture materials,” *Chemical Reviews*, vol. 112, pp. 724–781, 2012.
10. A. Goepfert et al., “Air capture of CO₂,” *Energy & Environmental Science*, vol. 5, pp. 7833–7853, 2012.
11. J. Wilcox, *Carbon Capture*, Springer, 2012.
12. R. Socolow, “Stabilization wedges,” *Science*, vol. 305, pp. 968–972, 2004.



© 2026 by the authors. Open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>)