Recent Advances and Trends in Carbon Dioxide Capture Technologies: A Review

Brij Mohan Sharma[1], Sandeep Kumar Bhaskar[2], Manu Augustine[3], Vinay Singh Marwal[4], Vikash Gautam[5,*]
[1,2,3,4,5]Department of Mechanical Engineering, Swami Keshvanand Institute of Technology, Management and Gramothan, Jaipur

*Corresponding author email:
E-mail: vikash.gautam@skit.ac.in

Abstract: The urgent need to combat climate change has placed carbon dioxide (CO_2) capture technologies at the forefront of environmental innovation. The paper begins by outlining the imperative for CO_2 capture, as global efforts intensify to mitigate climate change. It delves into a meticulous examination of various CO_2 capture methods, spanning established techniques such as post- and pre-combustion capture and cutting-edge solutions like direct air capture (DAC) and mineralization. The review synthesizes various sources to highlight the most recent findings and innovations in the field, including advancements in materials such as metal-organic frameworks and solid adsorbents that promise enhanced efficiency and cost-effectiveness. Moreover, it explores hybrid capture systems integrating multiple methods to optimize CO_2 removal. Environmental and sustainability considerations, as well as policy dynamics, are addressed in this article. The review underscores the significance of interdisciplinary approaches, including artificial intelligence and electrochemical CO_2 capture. It stresses the importance of international collaboration, funding initiatives, and developing smaller-scale, modular systems. In conclusion, this paper offers a comprehensive technical review of recent CO_2 capture advances, providing valuable insights for researchers, policymakers, and industry professionals working toward a sustainable and climate-resilient future.

Keywords: Climate Change, Sustainability, Carbon Dioxide Capture

1. Introduction

Carbon dioxide (CO_2) capture is pivotal in addressing the urgent challenge of climate change. With CO_2 being the primary greenhouse gas responsible for global warming, its unchecked release into the atmosphere from human activities, particularly the burning of fossil fuels, has driven the increase in global temperatures [1-3]. Climate change is an escalating global crisis, advancing faster than anticipated. It affects every corner of the world, triggering environmental degradation, natural disasters, extreme weather, food and water insecurity, economic upheaval, conflict, and terrorism. The consequences are evident, from rising sea levels and Arctic melting to dying coral reefs, acidifying oceans, and rampant forest fires. Business as usual is no longer an option, and urgent, collective action is imperative to address the escalating costs of climate change [4].

CO_2 capture technologies are of paramount importance because they provide a means to reduce greenhouse gas emissions. By capturing and preventing CO_2 from entering the atmosphere, these technologies help mitigate the greenhouse effect, stabilize global temperatures, and limit the severity of climate change impacts, including extreme weather events, sea-level rise, and disruption of ecosystems. CO_2 capture not only contributes to a transition to cleaner energy sources but also facilitates the development of a circular economy by converting captured CO_2 into valuable products, such as synthetic fuels, chemicals, and construction materials, thereby promoting carbon neutrality. Furthermore, CO_2 capture aligns with international climate agreements like the Paris Agreement, which sets global targets for limiting temperature increases [5]. It encourages innovation, research, and development in sustainable solutions, and it offers societies more time to adapt and build resilience in the face of changing climate conditions. In essence, CO_2 capture is a crucial tool in the comprehensive strategy to combat climate change and secure a more sustainable and resilient future.

The review brings together information from different sources to showcase the newest findings and innovations in the field for making CO_2 capture methods more efficient and cost-effective.

2. Methods used for Carbon Capture

CO_2 capture refers to trapping and isolating CO_2 from the emissions generated when fossil fuels are burned. The collected CO_2 is refined to yield a concentrated and pure stream of CO_2 that can be transported, utilized, or stored [6]. These CO_2 capture methods fall into three main groups [7, 8]: post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture. Figure 1.

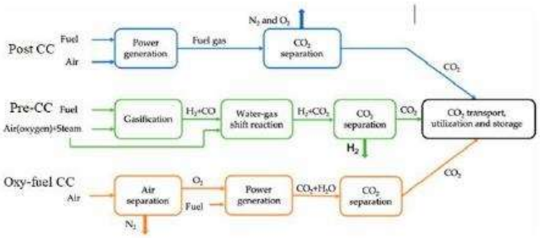

Fig. 1: Schematic diagrams of post-combustion capture (Post-CC), pre-combustion capture (Pre-CC), and oxy-fuel combustion capture (Oxy-fuel CC) [9].

2.1 Recent Methods Developed for Post-combustion Capture

Post-combustion CO_2 capture methods are based on removing carbon dioxide from flue gas. The capture unit is placed after the purification systems, such as desulphurization, denitrogenation, and dedusting installations. Figure 2 shows a general block diagram of the post-combustion capture technique.

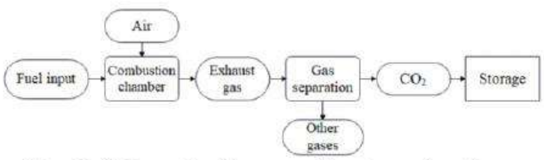

Fig. 2: Schematic diagram of post-combustion capture [10]

The recent advancement in post-combution capture methods are enlisted as given below:

Amine-Based Solvents [11]: Advancements in solvent-based systems, such as improved amines, for more efficient CO_2 absorption and regeneration.

Packed Bed Absorption [12]: Enhanced packed bed designs and materials to optimize CO_2 capture in post-combustion processes.

Membrane-Based Post-Combustion Capture [13]: The development of selective membranes that allow for the separation of CO_2 from flue gas.

Solid Sorbents [14]: Research into solid sorbent materials, like metal-organic frameworks (MOFs) and supported amine sorbents, which offer high CO_2 capture capacity.

Cryogenic Separation: Improvements in cryogenic distillation technology to separate CO_2 from flue gas at extremely low temperatures.

Electrochemical Post-Combustion Capture [15]: Development of electrochemical cells to capture CO_2 and convert it into useful products.

Hybrid Post-Combustion Capture Systems [16]: Combining different capture methods, such as membrane separation with solvent-based capture, for increased efficiency.

Sorbent-Enhanced Water-Gas Shift (SEWGS) [17]: Innovations in SEWGS technology for high-efficiency CO_2 capture in post-combustion applications.

Biological Post-Combustion Capture [18]: The use of biological systems like algae to capture CO_2 from flue gas.

Direct Air Capture (DAC) for Post-Combustion [19]: The application of DAC technology for capturing CO_2 from the atmosphere after combustion.

These recent developments aim to improve the energy efficiency, cost-effectiveness, and overall performance of post-combustion CO_2 capture methods, making them more practical and sustainable for various industrial and power generation applications.

2.2 Recent Methods Developed for Pre-combustion Capture

Pre-combustion capture focuses on removing CO before the combustion of fossil fuels (Figure 3). Fossil fuels are gasified and reformed by air and water vapor before combustion, eventually producing CO_2 and H_2. This includes a steam-reforming reaction to produce CO and H_2 and a water-gas shift reaction to convert CO to CO_2 [20]. The CO_2 and H_2 obtained from the reaction are separated by the gas separation method, and CO_2 is captured, while H_2 can be used as a fuel for hydrogen gas turbines.

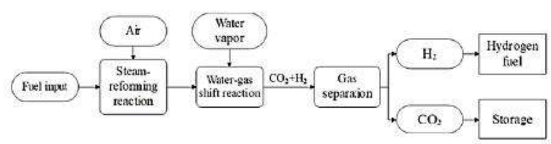

Fig. 3: Schematic diagram of pre-combustion capture [10]

Recent developments in pre-combustion CO_2 capture methods include:

Water-Gas Shift (WGS) Reaction Enhancement [21]: Advances in catalysts and reactor designs for more efficient conversion of carbonaceous fuels to hydrogen gas and CO_2, facilitating subsequent capture.

Chemical Looping Pre-Combustion Capture [22]: Development of chemical looping processes for pre-combustion CO_2 capture, using metal oxides to produce hydrogen with inherent separation of CO_2.

Solid Adsorbents for Pre-Combustion Capture [23]: Research into solid adsorbent materials, such as sorbents based on metal-organic frameworks (MOFs),

for efficient CO_2 removal in pre-combustion processes.
Pressure Swing Adsorption (PSA) [24]: Advancements in PSA technology for hydrogen separation and CO_2 capture in pre-combustion applications.
Polymeric Membrane Separation [25]: The development of selective membranes for separating hydrogen from syngas in pre-combustion capture.
Integrated Gasification Combined Cycle (IGCC) Systems [26]: Innovations in IGCC technology, which integrates gasification with CO_2 capture for more efficient power generation.
Sustainable Hydrogen Production using artificial photosynthesis [27]: Exploration of sustainable hydrogen production methods, such as using renewable energy sources in conjunction with pre-combustion capture.

These recent developments are aimed at enhancing the efficiency, cost-effectiveness, and environmental sustainability of pre-combustion CO_2 capture methods, particularly in applications like hydrogen production and integrated gasification systems.

2.3 Recent Methods Developed for Oxy-fuel Combustion Capture

Oxy-fuel combustion capture relies on the full combustion of fossil fuels in oxygen separated from the air to obtain CO_2, subsequently, CO_2 and water vapor and water vapor are separated by condensation and the captured CO_2 is stored as shown in Figure 4.

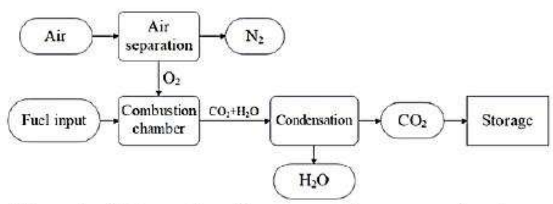

Fig. 4: Schematic diagram of pre-combustion capture [10]

Recent developments in oxy-fuel combustion capture methods include:

Advanced Oxy-Fuel Combustion Technologies [28]: Enhanced combustion processes that use oxygen instead of air to produce flue gases with a high CO_2 concentration.
Oxy-Fuel Boiler and Furnace Design [29]: Innovations in boiler and furnace designs to optimize the efficiency of oxy-fuel combustion and minimize nitrogen emissions.
Flue Gas Treatment and Cooling [30]: Advanced flue gas treatment and cooling technologies to remove impurities and water vapor, resulting in a high-purity CO_2 stream.
Integrated Oxy-Fuel Systems [31]: Advanced technology for integration of oxy-fuel combustion with carbon capture and storage (CCS) or carbon capture and utilization (CCU) processes to create more sustainable energy cycles.
Oxy-Combustion in Power Generation [32]: Advancements in oxy-fuel combustion for power generation, especially in coal-fired power plants, to reduce emissions and improve overall efficiency.
Integration with steam methane reformer (SMR) [33]: Shifting towards oxy-fuel combustion power cycles that simultaneously generate electricity and hydrogen offers a promising avenue for curbing carbon dioxide emissions from the energy sector. To attain a carbon-neutral outcome, this approach combines a semi-closed oxy-fuel combustion cycle with a steam methane reformer. This integration enhances overall energy efficiency by mitigating losses in the steam turbine condenser, ultimately working towards zero emissions from the process.

These recent developments in oxy-fuel combustion capture aim to make the process more energy-efficient, cost-effective, and environmentally sustainable, with applications in power generation and various industrial sectors.

4. Conclusion

In summary, this review paper underscores the vital role of carbon dioxide (CO_2) capture technologies in addressing climate change. It provides a comprehensive analysis of various CO_2 capture methods, ranging from established techniques like post- and pre-combustion capture to innovative solutions such as direct air capture and mineralization. The paper synthesizes the latest findings and innovations for promising increased efficiency and cost-effectiveness.

References

1) Solomon, S. (Ed.). (2007). Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC (Vol. 4). Cambridge university press.
2) McMichael, A. J., & Haines, A. (1997). Global climate change: the potential effects on health. Bmj, 315(7111), 805-809.
3) Hegerl, G. C., & Cubasch, U. (1996). Greenhouse gas induced climate change. Environmental Science and Pollution Research, 3, 99-102.
4) "The Climate Crisis – A Race We Can Win" https://www.un.org/en/un75/climate-crisis-race-we-can-win (accessed October 03, 2023).
5) "The Paris Agreement" https://unfccc.int/process-and-meetings/the-paris-agreement (accessed October 04, 2023).
6) Zhang, Z., Pan, S. Y., Li, H., Cai, J., Olabi, A. G., Anthony, E. J., & Manovic, V. (2020). Recent advances in carbon dioxide utilization.

Renewable and sustainable energy reviews, 125, 109799.

7) Ming, Z., Shaojie, O., Yingjie, Z., & Hui, S. (2014). CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis. Renewable and Sustainable Energy Reviews, 39, 604-616.

8) NETL, Carbon Dioxide Capture Approaches, U.S Department of Energy - National Energy Technology Laboratory, 2021. https://netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/capture-approaches
(accessed October 22, 2023).

9) Yao J, Han H, Yang Y, Song Y, Li G. A Review of Recent Progress of Carbon Capture, Utilization, and Storage (CCUS) in China. Applied Sciences. 2023; 13(2):1169. https://doi.org/10.3390/app13021169

10) Hua, W., Sha, Y., Zhang, X., & Cao, H. (2023). Research progress of carbon capture and storage (CCS) technology based on the shipping industry. Ocean Engineering, 281, 114929.

11) Liang, Z. H., Rongwong, W., Liu, H., Fu, K., Gao, H., Cao, F., ... & Tontiwachwuthikul, P. P. "Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents. International Journal of Greenhouse Gas Control, 40, 26-54 (2015).

12) Wojtasik-Malinowska, J., Piątkowski, M., Blatkiewicz, M., Jaskulski, M., Wawrzyniak, P., & Górak, A. Reactive absorption of carbon dioxide in aqueous n-methyldiethanoloamine solutions catalysed with carbonic anhydrase in a rotating packed bed (RPB). Chemical Engineering and Processing-Process Intensification, 184, 109266 (2023).

13) Olabi, A. G., Alami, A. H., Ayoub, M., Aljaghoub, H., Alasad, S., Inayat, A.,& Sayed, E. T. (2023). Membrane-based carbon capture: Recent progress, challenges, and their role in achieving the sustainable development goals. Chemosphere, 137996.

14) Rezaei, S., Liu, A., & Hovington, P. (2023). emerging technologies in post-combustion carbon dioxide capture & REMOVAL. Catalysis Today, 114286.

15) Ripley, K. M., & Brushett, F. R. (2023, August). Exploring Performance and Cost Trade-Offs in Electrochemical CO2 Separation Processes. In Electrochemical Society Meeting Abstracts 243 (No. 24, pp. 1614-1614). The Electrochemical Society, Inc.

16) Chatziasteriou, C. C., Georgiadis, M. C., & Kikkinides, E. S. (2023). Modeling and optimization of hybrid P/VSA-membrane separation processes for CO2 capture from post combustion flue gas. In Computer Aided Chemical Engineering (Vol. 52, pp. 2771-2776). Elsevier.

17) Cheng, L. B., Kim, J. Y., Ebneyamini, A., Li, Z. J., Lim, C. J., & Ellis, N. (2023). Thermodynamic modelling of hydrogen production in sorbent-enhanced biochar-direct chemical looping process. The Canadian Journal of Chemical Engineering, 101(1), 121-136.

18) Iglina, T., Iglin, P., & Pashchenko, D. (2022). Industrial CO2 capture by algae: a review and recent advances. Sustainability, 14(7), 3801.

19) Kothari, D. C., and Thorat, P. V. (2020). Direct Capture of CO2 from Air & Scale-Up it for Sustainable Developments.

20) Wang, H., Zhou, P. & Wang, Z. Reviews on current carbon emission reduction technologies and projects and their feasibilities on ships. J. Marine. Sci. Appl. 16, 129–136 (2017). https://doi.org/10.1007/s11804-017-1413-y

21) Baraj, E., Ciahotný, K., & Hlinčík, T. (2021). The water gas shift reaction: Catalysts and reaction mechanism. Fuel, 288, 119817.

22) Alalwan, H. A., & Alminshid, A. H. (2021). CO2 capturing methods: Chemical looping combustion (CLC) as a promising technique. Science of The Total Environment, 788, 147850.

23) Chen, Q., Rosner, F., Rao, A., Samuelsen, S., Jayaraman, A., & Alptekin, G. (2019). Simulation of elevated temperature solid sorbent CO2 capture for pre-combustion applications using computational fluid dynamics. Applied energy, 237, 314-325.

24) Luberti, M., & Ahn, H. (2022). Review of Polybed pressure swing adsorption for hydrogen purification. International Journal of Hydrogen Energy, 47(20), 10911-10933.

25) Han, Y., & Ho, W. W. (2021). Polymeric membranes for CO2 separation and capture. Journal of Membrane Science, 628, 119244.

26) Ren, S., Feng, X., & Wang, Y. (2021). Emergy evaluation of the integrated gasification combined cycle power generation systems with a carbon capture system. Renewable and Sustainable Energy Reviews, 147, 111208.

27) Nguyen, V. H., Nguyen, B. S., Jin, Z., Shokouhimehr, M., Jang, H. W., Hu, C., ... & Van Le, Q. (2020). Towards artificial photosynthesis: Sustainable hydrogen utilization for photocatalytic reduction of CO2 to high-value renewable fuels. Chemical Engineering Journal, 402, 126184.

28) Yadav, S., & Mondal, S. S. (2022). A review on the progress and prospects of oxy-fuel carbon capture and sequestration (CCS) technology. Fuel, 308, 122057.

29) Zhang, Y., Vangaever, S., Theis, G., Henneke, M., Heynderickx, G. J., & Van Geem, K. M. (2021). Feasibility of biogas and oxy-fuel

combustion in steam cracking furnaces: Experimental and computational study. Fuel, 304, 121393.

30) Cao, R., Ruan, R., Tan, H., Bai, S., Du, Y., & Liu, H. (2021). Condensational growth activated by cooling method for multi-objective treatment of desulfurized flue gas: A full-scale study. Chemical Engineering Journal, 410, 128296.

31) Portillo, E., Alonso-Fariñas, B., Vega, F., Cano, M., & Navarrete, B. (2019). Alternatives for oxygen-selective membrane systems and their integration into the oxy-fuel combustion process: A review. Separation and Purification Technology, 229, 115708.

32) Kindra, V. O., Komarov, I. I., Kharlamova, D. M., Naumov, V. Y., & Maksimov, I. A. (2023). Development and Investigation of the Advanced Oxy-Fuel Power Plants Equipment Preliminary Design. Thermal Engineering, 70(10), 736-750.

33) Kindra, V., Rogalev, A., Oparin, M., Kovalev, D., & Ostrovsky, M. (2023). Research and Development of the Oxy-Fuel Combustion Power Cycle for the Combined Production of Electricity and Hydrogen. Energies, 16(16), 5983.

34) Hua, W., Sha, Y., Zhang, X., & Cao, H. (2023). Research progress of carbon capture and storage (CCS) technology based on the shipping industry. Ocean Engineering, 281, 114929.