IAA Journal of Biological Sciences 13(2):39-46, 2025
©IAAJOURNALS
https://doi.org/10.59298/IAAJB/2025/1323946
www.iaajournals.org
ISSN:2636-7254
IAAJB132

Advancements in Carbon Capture and Storage Technologies

Muhindo Anitah

Department of Pharmacy Kampala International University Uganda
Email: anitah.muhindo@studwc.kiu.ac.ug

ABSTRACT

Carbon Capture and Storage (CCS) technologies have emerged as critical solutions in the global effort to reduce carbon dioxide (CO_2) emissions and mitigate climate change. This paper presents a comprehensive review of recent advancements in CCS technologies across various industrial sectors, including energy production, steel manufacturing, cement, and ammonia industries. It outlines the development of post-combustion, pre-combustion, and direct air capture methods, with a focus on innovative materials such as zeolites, ionic liquids, and solid sorbents. Geologic storage solutions, including saline aquifers and depleted oil reservoirs, are assessed for their capacity, reliability, and environmental safety. The paper also explores economic, regulatory, and infrastructural challenges facing large-scale CCS deployment and evaluates successful case studies, such as Sleipner in Norway and commercial initiatives in China and the UK. Despite progress, the adoption of CCS is hindered by high costs, energy penalties, and public perception. Future CCS research must prioritize cost-efficiency, scalability, and integrated policy frameworks to support the transition to a low-carbon economy.

Keywords: Carbon Capture and Storage (CCS), Post-Combustion Capture, Direct Air Capture (DAC), Carbon Sequestration, Climate Change Mitigation, CO_2 Utilization, Geologic Storage, Amine Absorption.

INTRODUCTION

In recent decades, rising carbon dioxide (CO2) emissions have motivated R&D efforts in advanced carbon capture, utilization, and storage (CCUS). Particularly in the energy sector, this technique is essential for attaining net-zero emissions. A broad overview of CCUS technology developments since 2015 is provided, and consequently, an outline of the detailed review papers on this topic is provided. In the energy production sector, considerable advancements in the post-combustion technology have been made, with the commercial technologies of absorption, adsorption, membrane, and ionic liquid-based separation and solid separation also available. Meanwhile, promising technology routes, such as calcium looping and zeolite-based membranes, deserve greater R&D efforts. Furthermore, the performance of a CCUS demonstration facility under the transition from a pilot plant to a commercial scale, and CCUS application in the cement industry are also reviewed. This review especially focuses on the innovative technologies developed for iron and steel and ammonia production. It is anticipated that the widespread commercialization of CCUS technology can work together with other emission reduction strategies to build a sustainable energy system. A drop in atmospheric carbon dioxide (CO2) concentration is required to stabilize the climate and reduce anthropogenic impacts. An overall reduction of about 4.3 GtCO2 /year in new emissions from a business-as-usual future is required. This includes the replacement of fossil fuels with renewable hydropower, wind, and advanced nuclear power to reduce energy consumption. The limitation of renewable and carbon-neutral biomass resources is such that even with huge advances in these technologies, fossil fuels will still account for 60% of global energy. Thus, a solution is needed for a situation where high emissions of CO2 due to high energy consumption are unavoidable. This solution may be called carbon capture and storage (CCS) [1, 2].

Historical Context of Carbon Capture Technologies

The post-combustion separation process, involving solvent-based removal of carbon dioxide from flue gases, is the most widely used method in industry. Research has focused on improving fixed-start absorption processes for CO2 removal. In the 21st century, novel methods utilizing new CO2 sorbents and structural innovations have emerged. These solutions vary based on gas types, sorbent materials, and apparatus designs. Some sorbents are already in large-scale commercial use, while others are in initial applications. Focusing on these new solutions may create niche market opportunities. For offshore greenhouse gas capture and storage, saline aquifers have been preferred for CO2 storage locations. However, concerns about leakage due to fault activity have led to suggestions for using depleted offshore oil reservoirs instead. Some fields have initiated injection trials to assess CO2 storage feasibility, benefiting from geological structures that resist fractures better than saline aquifers. The study aims to explore the mechanical equilibrium of a compressible fluid, similar in viscosity to carbon dioxide, influenced solely by a constant pressure gradient [3, 4].

Current Technologies in Carbon Capture

CCS technology is deployed at commercial scales internationally with a growing number of large-scale projects for industrial applications. Generally, CCS technology can be divided into three major categories: destination capture, abroad capture, and point source. Direct air capture (DAC) uses adsorption resin and amine to capture CO2 directly from the ambient air. The captured CO2 can be compressed and sequestered, or used for enhanced oil recovery (EOR), or turned into carbonate products like urea or carbonates. Post-combustion capture (PCC) is the capture of the effluent gases after fuels are burned. The commercial PCC technology uses chemical absorbers such as amines and adsorbents such as zeolites. Meanwhile, amine solvent is the most popular solvent, among which monoethanolamine (MEA) is the most used solvent and is the benchmark solvent for amine-based PCC technology. Amine suppression of CO2 post-combustion capture is a kinetic-controlled process that is limited by the mass transport of CO2. Therefore, the solvents need to be regenerated by heating up to 100°C, leading to simultaneous solvent degradation and energy penalty. Supercritical CO2 capture technology captures CO2 from the effused flue gas, and compresses it into a supercritical state so that it can be easily transported and sequestered underground. Generally, the separating process is a combination of chemical absorption, physical absorption, and dry purification. The CO2 post-combustion capture technology is a well-developed and commercial technology deployed for more than a hundred years in the global industry. Their during-gassing operation is highly automated, with supervision required to monitor only alarms and shutdown procedures. On the contrary, PCC with amine solvent carbon capture varies greatly, including a large number of unoptimised setups with the same combination of technologies, and their semi-batch mode operation incurs social cost on monitoring and debugging [5, 6].

Innovative Materials for Carbon Capture

Carbon dioxide (CO2), the primary greenhouse gas, is ubiquitous on Earth and arises from aerobic metabolism in most organisms. It is generated through various industrial activities that burn fossil fuels and biomass for energy and heat. Once emitted, CO2 traps infrared radiation from the Earth's surface, contributing to greenhouse gas formation. Current CO2 emissions are on the rise. To limit CO2 concentrations from pre-industrial levels of 280 ppm to 550 ppm by 2100, the International Panel on Climate Change targets a carbon offset of 50-850 Gtons, posing a significant challenge for society. Capturing carbon (as CO2) from major emitters like power plants and cement factories is seen as essential. The potential for carbon capture and storage (CCS) across industries offers a vast market for related equipment and services over the coming decades. CCS involves a complex process of capturing CO2 (the most expensive step), transporting it, and permanently storing it in geological formations. New large-scale capture technologies have shown promise, leading to significant research into efficient and cost-effective methods. This review will focus on notable processes for immediate post-combustion CO2 capture. After purification, CO2 can be transformed into chemicals such as urea or methanol, or used to create cleaner energy sources. Enhanced oil recovery (EOR), as a CO2 storage method, is also widely considered, often in conjunction with its utilization [7, 8].

Storage Methods for Captured Carbon

The methods for storing CO2 can be broadly classified into two categories: geologic storage and carbon utilization. Geologic storage methods include injection into deep saline aquifers, depleted oil reservoirs, underground coal seams, basalt formations, of transferred natural gas reservoirs. Disposal of CO2 into deep geological formations is a tried-and-tested concept, in which high-pressure water and gas are routinely stored in aquifers. Storage of CO2 in the pore spaces of geology is similar to the routine disposal of oilfield brines, as both fluids are fluids with very low density comparable to that of caprock. These formations are widely distributed and can hold even larger quantities of CO2 than depleted oil fields. According to recent estimates, CO2 is presently emitted by 1,037 potential emitters in the UK, including all major UK industrial sources and processes, fossil fuel power generation, major waste sites, and cement, hydrogen, ammonia, and other process emissions, totaling 278 million tonnes of CO2 (MtCO2) annually. Over 8 billion tonnes of CO2 are emitted in the EU and the UK annually, with only 0.01% captured and stored. The world's first commercial plant to capture and store CO2 was the Sasol Fischer-Tropsch plant in Mossel Bay, South Africa, in 1996, and has since stored over 5 million tonnes of CO2 at 1,000 m depth in the coastal sandstone aquifer. The largest anthropogenic storage site to date is Sleipner in the Norwegian North Sea, which has been monitoring 13 million tonnes per year for 25 years (since 1996), the world's first offshore, large-scale CO2 sequestration project. However, by 2019, 239 million tonnes of CO2 were stored annually, less than 1% of anthropogenic emissions. The geology of both Sleipner and San Andreas is typical of CO2 disposal, which relies on the difference in density and compressibility between CO2 and the brine already filling the pore spaces. The best remaining options for geologic storage are tight, gas-bearing rocks at depths exceeding 1,500 m [9, 10].

Economic Aspects of Carbon Capture

The deployment of carbon capture and storage (CCS) technologies is increasing, though costs for specific technologies are still changing. This emphasizes the diverse roles of each development within a techno-economic framework. Various designs were used for every capital-intensive step in a power plant focused on CO2 separation and storage. New processes were suggested, and more economically viable ones were tested for smaller applications. The studied CCS technology includes multipoint flue gas desulphurization, an amine-based CO2 capture step, and low-pressure multistage gas-liquid CO2 compression. Safety involves a brief explanation within a quantitative risk assessment framework, including screening, event trees, and flow diagrams, alongside health and safety studies and level 3 risk quantification. National regulatory differences arise from geology and historical vested interests. For example, the risks linked to abandoned North Sea gas fields contrast with the in-situ storage interest in the US. Experienced geologists in seismic imaging greatly outnumber less experienced ones regarding deep aquifers. The results of CO2-ECBM feasibility studies remain unpublished. Department of Energy policy focuses on deploying various CO2 sources across nations and testing simplified CO2 monitoring systems in field experiments. By the decade's end, it is anticipated that global comparisons and rankings of CO2 storage projects will emerge. The safety of coal storage relates to the natural permeability of CO2 migration, aiming for a pressure threshold to maintain a time horizon of up to 2000 years, based on wall rock permeability [11, 12].

Environmental Impact of Carbon Capture

This paper aims to introduce the various technologies for carbon capture and storage from gas emission sources into the Earth's soil. There is also a discussion on the shortcomings as well as the technological advancements in overcoming them. Technology for carbon capture from flue gases is already established, though still to be commonly accepted due to a few technological disadvantages, most notably the high energy consumption of the post-combustion capture techniques. However, this energy consumption is reduced with the new solid sorbing technologies currently being investigated, and less than one-third of the overall energy consumption is broken down with pre-combustion capture, switching from high energy consumption. Thermochemical has also been used not only to capture the carbon but also to convert it to ethanol or olivine, which sequesters the carbon in the soil too. High-learning-cost carbon capture and storage systems are expected to be a limitation to developing countries as the market for carbon credits becomes established. However, this barrier is decreasing with the emergence of emerging technologies. More R&D funding and encouragement for pilot projects are fundamental to the further development of a commercially viable, safe, and sustainable carbon capture and storage system. Carbon capture and storage is discussed as a solution that captures large quantities of carbon dioxide from the atmosphere and stores it in geologic formations. The aim is to introduce different options to cover the whole carbon capture and storage process from gas emission to the use or burying of the carbon compound [13, 14].

Case Studies of Successful Implementations

The technologies for Carbon Capture and Storage (CCS) have greatly progressed in the last decade and, in some areas, have reached important thresholds for implementation. PDOs are defined as activities, demonstration projects, and not necessarily full-scale plants, which allow further advancement in implementation and a better understanding of the opportunities that CCS provides to specific regional economies, industries, or technologies, be they existing or emerging ones. There are various methods of capturing CO2, including Pre-Combustion Capture, Fuel Cells, Post Combustion Capture, and Oxyfuel Combustion, and the list is still growing. Post-combustion capture is the focus of this section, as it includes the technology that has been adopted for the greatest number of plants and is believed to be the most commercially ready technology for the long-term sustainable economic reduction of power sector carbon emissions. In Europe, the current interest in Post-combustion Capture (PCC) stems from ongoing and committed to a total of 18.9 million tonne/year CO2 capture in the 73 legacy plants, whose number and total capacity are still growing. In the UK, it is noteworthy that 80% of the deployment plans are based on PCC with chemical absorption. Consequently, much of this section will be about PCC with chemical absorption, although there will be references to research activity and pilot and demonstration plants based on other types of technology. In Asia, and particularly China, there are some plants of a scale greater than 100,000 tonne CO2/year in operation or committed, including 3 post-combustion capture units by Luan Group, Yunnan Yuntianhua completed in mid-2011 and Tianguang Power Plant and Xuan Wei Industrial Park which are expected to be operational before the end of 2012. At present, 340,400 tonne/year of CO2 capture is operated or under commissioning in China [15, 16].

Challenges and Barriers to Adoption

The rise of renewable energy and energy-efficient technologies is expected to reduce reliance on fossil fuels, although this may take longer than anticipated. Conversely, carbon capture technologies could help lower atmospheric carbon levels short term. Given the inherent uncertainties of developing new technologies, it's essential to evaluate a broad range of low-carbon options based on factors like time, feasibility, and costs. This evaluation will identify successful strategies and highlight unviable technologies. For instance, potential futures for carbon capture, utilization, and storage (CCUS) in electric power, industry, and transportation are discussed. Political resistance to phasing out fossil fuels remains strong, with extraction likely limited to approved reserves. Thus, carbon capture technologies are critically needed. Currently, fossil fuel carbon exists in vast geological coal deposits and oil and gas reservoirs. Daily global coal consumption for heating and power emphasizes the ongoing reliance on fossil fuels. Despite advancements in renewables, fossil fuel extraction will continue to appeal due to supply and price fluctuations, even as public concern over increased greenhouse gas emissions rises. Historical trends indicate a growing emphasis on addressing this concern through carbon capture innovations. However, foundational societal and scientific structures largely depend on fossil fuels, necessitating economic incentives for change. There are various carbon capture technologies, some of which can build upon existing processes. Still, some will require significant development time and may not be viable in the short term. An assessment framework for low-carbon options incorporates both skeptical and optimistic views on technological success [17, 18].

Future Directions in Carbon Capture Research

The post-combustion capture (PCC) of CO2 from the flue gas of traditional coal combustion power plants is the most studied and commercialized technology for carbon capture and sequestration (CCS). With an optimistic view, it can be expected that PCC technologies will soon be used at scale in new coal and gas power plants in combination with carbon storage. The development of PCC technologies is subject to the usual technology development challenges of cost and efficiency. Although several incremental improvements may be anticipated, getting cost and efficiency on a par with the rest of the energy conversion chain will be more difficult. Nevertheless, the most studied PCC technology, the amine capture process, is now sufficiently developed that a first wave of plants is likely to be built shortly. Improved regulator frameworks are needed to develop large-scale and low-cost infrastructure for CO2 transport, monitoring, and storage, where storage is often the greatest scientific challenge. Awareness of the necessity of CCS in climate policy is growing, and attractive funding opportunities are emerging in many countries. Great expectations are placed on CCS to contribute significantly to global greenhouse gas emission reduction targets. The technical challenge is, however, daunting. Meaningful reductions in anthropogenic CO2 emissions can only be achieved if CCS technologies can be developed for many, widely distributed, fixed point sources rapidly and at low cost. Only a tiny fraction of all sources will be able to store CO2 on site. Storage will need to be at sedimentary basins connected to many sources with long-distance transport schemes. There is a history of sometimes adverse public attitudes to large-scale infrastructure projects that create environmental uncertainty. These are required for public acceptance, legal systems, and engineering know-how to be developed for some CCS sites decades before actual plans for capture are considered [19, 20].

Regulatory Framework Surrounding Carbon Capture

The United States (U.S.) economy depends largely on energy recovery from fossil fuels, mainly coal and natural gas. With the known reserves of both fuels, together with current and anticipated conditions in domestic and foreign markets, the trend towards their increased use is likely to continue. Despite the continued development of renewable energy sources, it is unlikely that their market penetration will increase sufficiently shortly to prevent an increase in the atmospheric concentration of CO2, especially when combined with energy consumption increases from the developing world. Because increasing CO2 levels have been strongly implicated in global warming, and because no feasibly deployable options for its large-scale removal once emitted are anticipated to be developed quickly enough to address climate change, researchers and engineers are focusing on technologies for capturing CO2 from source points before it enters the atmosphere. Over the past decade or so, CO2 capture technologies of various styles and types have been demonstrated at many laboratory and pilot scales. The conversion of captured CO2 to useful products with large markets that would drive technological and economic development, and the mitigation of the problem of CO2 disposal, have recently received increased interest. Additionally, the intermediate problem of transportation of the CO2 from the source point, where it is at high pressure, high temperature and with large flow rates, will not be technologically nor economically feasibly solved unless and until a highly regulated, monitored and controlled sink point, such as depleted oil and gas fields or deep saline aquifers with large pore space, is developed. Emissions trading networks with an active non-fossil fuel energy resource marketplace, successfully facilitating the broad and efficacious implementation and coordination of a global full portfolio of climate-changing gas mitigation technologies, will most likely be necessary. Doing so in a balkanized, politically and socially conflicted world is a great technological challenge. Nonetheless, developing first a lower-cost, lower technology risk capture system that could be added to existing coal power plants is desirable for tackling this major problem. While the focus of carbon capture has shifted to post-combustion capture, as the new technology developments are generally thought to be riskier than modifying a system that is already well-designed and known [21, 22].

Role of Carbon Capture in Climate Mitigation

Energy expansion and population rise across the world lead to CO2 release into the atmosphere and an increase in global temperatures. It has been observed that the lifetime of CO2 in the atmosphere is very long, indicating a long-term impact on global warming and climate change. To mitigate climate change, it is required to decrease CO2 emissions. The steep temperature rise limited to 1.5 °C above the pre-industrial level can be met by curtailing fossil fuel production and use. However, the effects of climate change are already felt across the globe, and hence, it is required to remove existing carbon dioxide from the atmosphere as well as prevent further emissions into the atmosphere, especially from fossil fuel high-emission sectors like cement, steel, and utility generation. Industrial carbon dioxide emissions were first reported in 1976. Since then, many carbon capture and storage technologies have been investigated. Carbon capture, usage, and storage, hereafter referred to as CCS, remains the main tactic to fight climate change. Fossil fuel CO2 generation sequestration is either naturally or strongly buffered compared to desired man-made emissions. Carbon capture technologies include pre-combustion capture, post-combustion capture, direct air capture, absorption, cryogenic liquification, membrane separation, and adsorption. Geological and mineral carbon dioxide storage options are also discussed. Research history, current primary carbon capture and storage methods, electrochemical CO2 sorbent regenerations, carbon capture and storage in 2100 and 2030 net-zero designs, carbon capture and storage advancements via bioengineering methods, and magnetic and porous materials are discussed. It is hoped this review will inspire researchers to further investigate carbon capture and storage technologies. Advanced carbon-capturing method options include catalytic removal of CO2 from fossil fuels and other processes. A cooperating pilot plant will need to 75% capture. Idealized Amine extraction in a simple gas separation in the Allison testing framework is also discussed to be scalable and facilitate infrastructure support design [23, 24].

Integration with Renewable Energy Sources

Integrating carbon capture and storage (CCS) technologies with renewable energy sources (RES) such as solar and wind power can have a number of benefits, including increased efficiency in carbon capture, improved energy efficiency, and improved economics. Currently, the two technologies operate independently, which results in wasted energy and other inefficiencies. Therefore, there is much that can be gained from better integrating CCS and RES technologies. In standalone applications, RES and CCS operate separately, with RES, such as solar or wind, generating clean electricity that would be available to green energy-consuming facilities. In many cases, this includes energy-intensive CCS facilities that use fossil fuels to generate the energy necessary for capturing carbon and transporting waste. Though there are many existing and proposed standalone RES and CCS facilities, it has been shown that integrating the two technologies allows direct use of RES energy, achieving higher carbon capture efficiency (and therefore greater carbon capture) while costing less. Furthermore, experiments and existing sites indicate that RES and CCS can reliably operate together. Integration can be achieved by coupling either a grid-scale renewable electricity source to an industrial energy consumer or by industrial energy consumers locating themselves adjacent to renewable energy sources. Research has documented examples of integrated RES-CCS facilities, such as how a solar plant in Morocco and a solar farm powering a reverse osmosis desalination plant in South Africa are more efficient and reduce costs and carbon emissions than deploying the technologies separately. However, modeling work comparing fully integrated RES-CCS installations with separate RES and CCS deployments has yet to be undertaken. Such integrated modeling of the interplay between energy demand, energy generation, and carbon capture is essential for both identifying and realizing opportunities for impactful synergies between these technologies. Fully understanding and quantifying this integrated interaction can better enable RES-CCS projects to be deployed and scaled up [25, 26].

Public Awareness and Education

Public awareness is a precondition for public acceptance. Individuals are informed about environmental issues in a variety of ways, ranging from social media and word-of-mouth to establishment reports, specialized reports addressing an enlightened public, and newscasts. But how effective is this communication and information transmission in a practical sense? Green issues can only succeed if the communication is targeted and reaches the specified audience. A two-step approach can be taken to evaluate communication in terms of these parameters for CCS. The first is the assessment of the traditional comparative analysis of public acceptance in the same way across the board. The second step would go deeper into the various studies to reveal the of CCS campaigns success or failure? Suffice it to say here that despite the wealth of data collected and analyzed in the early years of the French CCS campaign, it became ever so clear that each of the stakeholders was talking about something else because of the disconnect between their various views on the CCS project. A traditional method used in the Hindi milieu for decades, Kalayuaya, was used quite successfully to address the varying views of the various stakeholders in the same project. This was preceded by the initial campaign analysis conducted by the French Research and Technology Institute on their 2007 campaign, which was done on behalf of the institutional stakeholders. This was essentially a general indicator study that required a multi-modal methodology. It consisted of diffusion maps, long social surveys, hot questionnaire jocopanels focused on 60 locations, and the media analysis of the national French newspapers examining the premises of the editorial stance, as well as a plethora of sustainability criteria on the various monthly, quarterly, and alternative sounding issue-based magazines. It is proposed to build on this campaign foundation and conduct campaign effectiveness audits using the IVED methods in the context of this research [27, 28].

CONCLUSION

Advancements in carbon capture and storage technologies have significantly broadened the prospects for reducing atmospheric CO_2 levels. The development of innovative materials and capture methods, coupled with growing experience in geologic storage, indicates that CCS can play a central role in achieving net-zero emissions. While notable progress has been made in demonstration projects and commercial deployments, widespread adoption remains limited by high capital costs, energy demands, and public skepticism. For CCS to become a viable climate strategy, it must be supported by robust regulatory frameworks, financial incentives, and continued research investment. Future efforts should focus on improving capture efficiency, expanding storage infrastructure, and fostering global collaboration to integrate CCS into broader decarbonization pathways. When strategically deployed, CCS stands as a critical bridge between today's fossil fuel-dependent energy systems and a sustainable, low-carbon future.

REFERENCES

1. Raganati F, Ammendola P. CO2 post-combustion capture: a critical review of Current technologies and future directions. Energy & Fuels. 2024 Jul 15;38(15):13858-905.
2. Hosseinzadeh-Bandbafha H, Panahi HK, Dehhaghi M, Orooji Y, Shahbeik H, Mahian O, Karimi-Maleh H, Kalam MA, Jouzani GS, Mei C, Nizami AS. Applications of nanotechnology in biodiesel combustion and post-combustion stages. *Renew Sust Energ Rev.* 2023 Aug 1;182:113414.

3. Liu RS, Shi XD, Wang CT, Gao YZ, Xu S, Hao GP, Chen S, Lu AH. Advances in post-combustion CO_2 capture by physical adsorption: from materials innovation to separation practice. *ChemSusChem.* 2021 Mar;14(6):1428–1471.
4. Gkotsis P, Peleka E, Zouboulis A. Membrane-based technologies for post-combustion CO2 capture from flue gases: Recent progress in commonly employed membrane materials. Membranes. 2023 Dec 2;13(12):898.
5. Kearns D, Liu H, Consoli C. Technology readiness and costs of CCS. Global CCS institute. 2021 Mar;3.
6. Shen M, Hu Z, Kong F, Tong L, Yin S, Liu C, Zhang P, Wang L, Ding Y. Comprehensive technology and economic evaluation based on the promotion of large-scale carbon capture and storage demonstration projects. *Rev Environ Sci Bio/Technol.* 2023 Sep;22(3):823–845.
7. Massagony A, Budiono. Is the environmental Kuznets curve (EKC) hypothesis valid on CO_2 emissions in Indonesia? *Int J Environ Stud.* 2023 Jan 2;80(1):20–31.
8. Nguyen XP, Hoang AT, Ölçer AI, Huynh TT. A record decline in global CO_2 emissions prompted by the COVID-19 pandemic and its implications on future climate change policies. *Energy Sources A.* 2025 Dec 31;47(1):4699–4702.
9. Furre AK, Warchoł MJ, Alnes H, Pontén AS. Sleipner 26 years: how well-established subsurface monitoring work processes have contributed to successful offshore CO_2 injection. *Geoenergy.* 2024 Dec 31;2(1):geoenergy2024-015.
10. Lloyd C, Huuse M, Barrett BJ, Stewart MA, Newton AM. A regional CO_2 containment assessment of the northern Utsira Formation seal and overburden, northern North Sea. *Basin Res.* 2021 May 24;33(3):1985–2017.
11. Davoodi S, Al-Shargabi M, Wood DA, Rukavishnikov VS, Minaev KM. Review of technological progress in carbon dioxide capture, storage, and utilization. *Gas Sci Eng.* 2023 Sep 1;117:205070.
12. Dziejarski B, Krzyżyńska R, Andersson K. Current status of carbon capture, utilization, and storage technologies in the global economy: a survey of technical assessment. *Fuel.* 2023;344:127946.
13. Kazemifar F. A review of technologies for carbon capture, sequestration, and utilization: cost, capacity, and technology readiness. *Greenhouse Gases Sci Technol.* 2022;12(5):923–951.
14. Shen M, Tong L, Yin S, Liu C, Wang L, Feng W, Ding Y. Cryogenic technology progress for CO_2 capture under carbon neutrality goals: a review. *Sep Purif Technol.* 2022 Oct 15;299:121734.
15. Osman AI, Hefny M, Abdel Maksoud MI, Elgarahy AM, Rooney DW. Recent advances in carbon capture, storage and utilization technologies: a review. *Environ Chem Lett.* 2021 Apr;19(2):797–849.
16. Wilberforce T, Olabi AG, Sayed ET, Elsaid K, Abdelkareem MA. Progress in carbon capture technologies. *Sci Total Environ.* 2021 Mar 20;761:143203.
17. Wilberforce T, Baroutaji A, Soudan B, Al-Alami AH, Olabi AG. Outlook of carbon capture technology and challenges. Science of the total environment. 2019 Mar 20;657:56-72.
18. Viebahn P, Jean Louis Chappin E. Scrutinising the gap between the expected and actual deployment of carbon capture and storage: a bibliometric analysis. *Energy Procedia.* 2018;148:874–881.
19. Materazzi M, Chari S, Sebastiani A, Lettieri P, Paulillo A. Waste-to-energy and waste-to-hydrogen with CCS: methodological assessment of pathways to carbon-negative waste treatment from an LCA perspective. *Waste Manag.* 2024 Jan 1;173:184–199.
20. Raganati F, Miccio F, Ammendola P. Adsorption of carbon dioxide for post-combustion capture: a review. *Energy Fuels.* 2021;35(16):12845–12868. pubs.acs.org+4energy.gov+4iris.cnr.it+4
21. Garcia JA, Villen-Guzman M, Rodriguez-Maroto JM, Paz-Garcia JM. Technical analysis of CO_2 capture pathways and technologies. *J Environ Chem Eng.* 2022 Oct 1;10(5):108470.
22. Lin Q, Zhang X, Wang T, Zheng C, et al. Technical perspective of carbon capture, utilization, and storage. *Engineering.* 2022;14:21–32.
23. Gong G, Zhang J, Teng Y, Li Q, Yang M, Zheng JN, Chen B, Song Y. Laboratory-scale studies on the effect of promoters on CO2 capture and sequestration via hydrate method: A comprehensive review. Energy Reviews. 2024 Mar 30:100086.
24. Signorini V, Muthukamatchi A, Ansaloni L, Peters TA, Alcock B, Fiorini M, Giacinti Baschetti M, Minelli M. Physical, mechanical, and thermal characterization of the elastomer response to

high-pressure CO_2 for use in carbon capture and storage applications. *Ind Eng Chem Res.* 2025 Mar 11;64(12):6704–6716.

25. Filippov SP. The economics of carbon dioxide capture and storage technologies. *Thermal Eng.* 2022;69(6):389–399.
26. Grant N, Hawkes A, Napp T, Gambhir A. Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. *One Earth.* 2021;4(11):1535–1544.
27. Vasilev Y, Cherepovitsyn A, Tsvetkova A, Komendantova N. Promoting public awareness of carbon capture and storage technologies in the Russian Federation: a system of educational activities. *Energies.* 2021 Mar 4;14(5):1408.
28. Mulyasari F, Harahap AK, Rio AO, Sule R, Kadir WG. Potentials of the public engagement strategy for public acceptance and social license to operate: case study of carbon capture, utilisation, and storage Gundih Pilot Project in Indonesia. *Int J Greenh Gas Control.* 2021 Jun;108:103312.

CITE AS: Muhindo Anitah (2025). Advancements in Carbon Capture and Storage Technologies. IAA Journal of Biological Sciences 13(2):39-46. https://doi.org/10.59298/IAAJB/2025/1323946