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# Advances in $CO_2$ injection and monitoring technologies for improved safety and efficiency in CCS projects

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## Abstract

Carbon Capture and Storage (CCS) is a critical technology for mitigating climate change by reducing greenhouse gas emissions. Recent advancements in $CO_2$ injection and monitoring technologies have significantly enhanced the efficiency and safety of CCS projects. Innovations such as supercritical $CO_2$ injection, intelligent injection systems, and foamed $CO_2$ have improved the storage capacity and distribution within geological formations. Monitoring technologies like time-lapse (4D) seismic monitoring, satellite imaging, distributed acoustic sensing (DAS), and chemical tracers provide high-resolution, real-time data, ensuring the secure containment of $CO_2$. Continuous technological development is vital for overcoming existing challenges and reducing costs associated with CCS projects. It also plays a crucial role in building public trust, securing regulatory approval, and ensuring long-term environmental safety. By advancing these technologies, CCS can become more economically viable and scalable, making it an integral part of global efforts to achieve carbon neutrality. The role of CCS in combating climate change is substantial, offering a complementary solution to renewable energy initiatives. With ongoing innovations and strategic investments, CCS has the potential to significantly reduce industrial $CO_2$ emissions, contributing to a sustainable and low-carbon future. Carbon Capture and Storage (CCS) is a critical technology for mitigating climate change by reducing greenhouse gas emissions. Recent advancements in $CO_2$ injection and monitoring technologies have significantly enhanced the efficiency and safety of CCS projects. Innovations such as supercritical $CO_2$ injection, intelligent injection systems, and foamed $CO_2$ have improved the storage capacity and distribution within geological formations. Monitoring technologies like time-lapse (4D) seismic monitoring, satellite imaging, distributed acoustic sensing (DAS), and chemical tracers provide high-resolution, real-time data, ensuring the secure containment of $CO_2$. Continuous technological development is vital for overcoming existing challenges and reducing costs associated with CCS projects. It also plays a crucial role in building public trust, securing regulatory approval, and ensuring long-term environmental safety. By advancing these technologies, CCS can become more economically viable and scalable, making it an integral part of global efforts to achieve carbon neutrality. The role of CCS in combating climate change is substantial, offering a complementary solution to renewable energy initiatives. With ongoing innovations and strategic investments, CCS has the potential to significantly reduce industrial $CO_2$ emissions, contributing to a sustainable and low-carbon future. Robust regulatory frameworks and public engagement are essential to maximize its impact.

**Keywords:** Carbon Capture and Storage (CCS); $CO_2$ injection; Monitoring technologies; Climate change mitigation; Supercritical $CO_2$; Real-time data analysis

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## 1. Introduction

Carbon Capture and Storage (CCS) is a pivotal technology in the global strategy to combat climate change (Adama and Okeke, 2024). By capturing $CO_2$ emissions from industrial sources and securely storing them underground, CCS prevents the release of this greenhouse gas into the atmosphere, thereby reducing the overall concentration of $CO_2$ and mitigating global warming. CCS is particularly crucial for sectors like cement, steel, and power generation, which are difficult to decarbonize through renewable energy alone (Adama and Okeke, 2024).

Two critical components underpin the effectiveness of CCS: the injection and monitoring of $CO_2$ (Ekechi et al., 2024). The injection process involves transporting captured $CO_2$ to a suitable geological formation, such as depleted oil and gas fields or deep saline aquifers, and injecting it into the subsurface. The success of this phase hinges on ensuring that $CO_2$ is stored efficiently and that the integrity of the storage site is maintained (Akinsanya et al., 2024). Monitoring technologies are essential for verifying that $CO_2$ remains securely stored and does not leak into the atmosphere or contaminate groundwater (Akinsanya, 2024).

Effective monitoring involves a combination of methods to track the movement and behavior of $CO_2$ in the storage site over time (Popoola et al., 2024). This includes using seismic surveys, satellite observations, and chemical tracers to detect any anomalies that could indicate potential leaks The outline aims to explore recent advancements in $CO_2$ injection and monitoring technologies, which have significantly enhanced the safety and efficiency of CCS projects. These advancements include innovative injection techniques, such as the use of supercritical $CO_2$ and foamed $CO_2$, which improve storage capacity and reduce the risk of leakage (Adama et al., 2024).

Intelligent injection systems that adapt to real-time data further optimize the injection process. In terms of monitoring, advances in seismic imaging, satellite technology, distributed acoustic sensing, and chemical tracers have greatly improved the ability to detect and respond to potential issues (Akinsanya et al., 2024). These technologies provide high-resolution, real-time data, ensuring the long-term security of $CO_2$ storage sites. By delving into these recent technological developments, the outline will highlight how CCS projects can be more effectively managed, enhancing their role in the fight against climate change

## 2. Advances in $CO_2$ Injection Technologies

Carbon Capture and Storage (CCS), Addressing $CO_2$ Injection Challenges with Advanced Techniques Carbon Capture and Storage (CCS) is a pivotal technology for reducing greenhouse gas emissions, capturing $CO_2$ from industrial sources, and securely storing it underground. However, $CO_2$ injection into geological formations presents significant technical and operational challenges. Ensuring the long-term storage of $CO_2$ demands a deep understanding of the geological formations, including their capacity, integrity, and potential for leakage (Ekechi et al., 2024).

Reservoir integrity is crucial for successful CO2 storage. The caprock, an impermeable layer above the storage reservoir, must remain intact to prevent $CO_2$ from escaping. Any fractures or faults in the caprock can lead to leakage, undermining the entire storage process. Ensuring caprock integrity involves thorough geological assessments and continuous monitoring to detect and mitigate any potential breaches (Popoola et al., 2024). Injecting large volumes of $CO_2$ increases the pressure within the reservoir. If not managed properly, this pressure can induce seismic activity or cause the caprock to fracture, leading to potential $CO_2$ leakage (Adama et al., 2024).

Effective pressure management requires sophisticated modeling and monitoring techniques to maintain reservoir stability and prevent adverse geological impact .Continuous monitoring and verification are essential for detecting leaks or $CO_2$ migration outside the intended storage area (Akinsanya et al., 2024). This involves the use of advanced monitoring technologies such as seismic surveys, satellite observations, and chemical tracers. Reliable data interpretation is crucial for timely detection and response to any anomalies, ensuring the long-term security of $CO_2$ storage sites. Geological formations are inherently heterogeneous, with variations in rock composition, porosity, and permeability (Popoola et al., 2024).

These variations can affect the distribution and movement of injected $CO_2$, making it difficult to predict and control. Addressing this challenge requires detailed geological characterization and adaptive injection strategies to ensure uniform $CO_2$ distribution and effective storage (Adama et al., 2024). To address these challenges, several advanced $CO_2$ injection techniques have been developed, enhancing the efficiency and safety of $CO_2$ storage. Supercritical $CO_2$ is $CO_2$ that has been compressed and heated above its critical temperature (31.1°C) and pressure (73.8 bar), where it exhibits properties of both a liquid and a gas. In this state, $CO_2$ has a higher density and lower viscosity compared to its gaseous form (Akinsanya, 2024).

The unique properties of supercritical $CO_2$ make it particularly suitable for injection into geological formations. Its higher density allows for more $CO_2$ to be stored in a given volume of the reservoir (Adama and Okeke, 2024). The lower viscosity of supercritical $CO_2$ enhances its ability to flow through porous rock formations, improving penetration and distribution within the reservoir. These properties help maximize storage efficiency and minimize leakage risks by ensuring more uniform displacement of the in-situ fluids. Intelligent injection systems leverage advanced sensors and data analytics to optimize the injection process.

These systems continuously monitor parameters such as pressure, temperature, and $CO_2$ flow rates in real-time. Using the data collected, intelligent systems can adjust the injection rate and pressure dynamically to adapt to changing reservoir conditions. This real-time adjustment helps maintain caprock integrity and prevent fracturing. It also ensures efficient $CO_2$ injection, improving overall storage capacity and safety (Chukwurah et al., 2024). Foamed $CO_2$ has a higher viscosity than supercritical $CO_2$, helping control flow and improve sweep efficiency. The foam spreads more evenly through the reservoir, reducing the risk of bypassing certain areas and ensuring uniform $CO_2$ distribution. This leads to better utilization of storage space and enhances the overall effectiveness of the CCS process (Ekechi et al., 2024).

## 3. Advances in Monitoring Technologies

Effective monitoring is critical for the success of Carbon Capture and Storage (CCS) projects, ensuring the long-term containment and safety of stored $CO_2$. Monitoring provides verification that $CO_2$ remains securely sequestered in geological formations and does not leak into the atmosphere or contaminate groundwater. This is essential for gaining public trust, regulatory approval, and ensuring the environmental integrity of CCS initiatives. Robust monitoring systems help detect potential leaks early, enabling timely intervention and preventing significant environmental impacts (Nzeako et al., 2024).

Continuous monitoring also provides valuable data to optimize injection strategies and improve the overall efficiency and safety of CCS operations (Nzeako et al., 2024). Recent advancements in monitoring technologies have significantly enhanced the ability to track and ensure the safe storage of $CO_2$ in CCS projects (Ochulor et al., 2024). These innovations offer more precise, real-time data, covering larger areas at reduced costs. Time-lapse (4D) seismic monitoring involves conducting repeated seismic surveys over time to create dynamic models of the $CO_2$ plume within the reservoir (Jambol et al., 2024).

This technique allows for the observation of changes in the subsurface caused by the injection of $CO_2$, providing critical information on the movement and behavior of the $CO_2$ plume. By comparing seismic data over different time intervals, operators can detect any deviations from expected $CO_2$ paths, indicating potential leakage or unforeseen interactions with geological features. Recent advances in seismic imaging and processing have significantly improved the resolution and accuracy of subsurface models. Enhanced algorithms and computational power enable better visualization of the $CO_2$ plume, even in complex geological settings.

High-resolution seismic imaging allows for the detailed mapping of geological formations, helping identify and mitigate potential risks associated with $CO_2$ storage. Satellite monitoring has become an integral part of CCS monitoring strategies, leveraging hyper spectral and thermal imaging sensors to detect changes in surface conditions that may indicate $CO_2$ leakage. Hyperspectral imaging captures a wide range of wavelengths, providing detailed information on the composition of surface materials. Thermal imaging detects temperature anomalies that could be associated with $CO_2$ escaping from the subsurface (Ukato et al., 2024).

The primary advantage of satellite monitoring is its ability to cover vast areas quickly and cost-effectively. Satellites can repeatedly survey large and remote areas, providing continuous data without the need for extensive ground-based infrastructure (Ukato et al., 2024) other localized monitoring techniques. Distributed Acoustic Sensing (DAS) uses fiber optic cables to detect acoustic signals generated by $CO_2$ movement within the reservoir. When $CO_2$ is injected, it generates acoustic waves that are captured by the fiber optic cables, which act as sensors along their entire length (Ochulor et al., 2024).

DAS technology provides high-resolution, real-time data on $CO_2$ flow and reservoir conditions. It can cover extensive areas with minimal physical infrastructure, offering detailed insights into the behavior of CO2 in the subsurface (Simpa et al., 2024). This technology is particularly useful for monitoring the integrity of injection wells and detecting early signs of leakage. Chemical tracers involve injecting small quantities of detectable chemicals along with $CO_2$. These tracers have distinct signatures that can be identified and measured even at low concentrations, allowing for precise tracking of $CO_2$ movement (Solomon et al., 2024).

The use of chemical tracers enables highly accurate tracking of $CO_2$ migration within the reservoir (Obasi et al., 2024). If $CO_2$ begins to move outside the intended storage area, the tracers can be detected at monitoring wells or surface stations, providing early warning of potential leaks. This method enhances the reliability of monitoring systems and supports timely interventions to address any issues (Simpa et al., 2024).

## 4. Importance of Effective Monitoring for CCS Projects

Effective monitoring is critical for the success of Carbon Capture and Storage (CCS) projects, ensuring the long-term containment and safety of stored $CO_2$. Monitoring provides verification that $CO_2$ remains securely sequestered in geological formations and does not leak into the atmosphere or contaminate groundwater (Solomon et al., 2024). This is essential for gaining public trust, regulatory approval, and ensuring the environmental integrity of CCS initiatives. Robust monitoring systems help detect potential leaks early, enabling timely intervention and preventing significant environmental impacts (Solomon et al., 2024).

Continuous monitoring also provides valuable data to optimize injection strategies and improve the overall efficiency and safety of CCS operations. Recent advancements in monitoring technologies have significantly enhanced the ability to track and ensure the safe storage of $CO_2$ in CCS projects. These innovations offer more precise, real-time data, covering larger areas at reduced costs (Adenekan et al., 2024). Time-lapse (4D) seismic monitoring involves conducting repeated seismic surveys over time to create dynamic models of the $CO_2$ plume within the reservoir (Simpa et al., 2024).

This technique allows for the observation of changes in the subsurface caused by the injection of CO2, providing critical information on the movement and behavior of the $CO_2$ plume (Digitemie and Ekemezie, 2024. By comparing seismic data over different time intervals, operators can detect any deviations from expected $CO_2$ paths, indicating potential leakage or unforeseen interactions with geological features. Recent advances in seismic imaging and processing have significantly improved the resolution and accuracy of subsurface models.

Enhanced algorithms and computational power enable better visualization of the $CO_2$ plume, even in complex geological settings. High-resolution seismic imaging allows for the detailed mapping of geological formations, helping identify and mitigate potential risks associated with $CO_2$ storage. Satellite monitoring has become an integral part of CCS monitoring strategies, leveraging hyperspectral and thermal imaging sensors to detect changes in surface conditions that may indicate CO2 leakage. Hyperspectral imaging captures a wide range of wavelengths, providing detailed information on the composition of surface materials (Igbinenikaro, 2024).

Thermal imaging detects temperature anomalies that could be associated with $CO_2$ escaping from the subsurface. The primary advantage of satellite monitoring is its ability to cover vast areas quickly and cost-effectively (Ekemezie and Digitemie, 2024). Satellites can repeatedly survey large and remote areas, providing continuous data without the need for extensive ground-based infrastructure. This makes it an efficient tool for baseline studies and ongoing monitoring, complementing other localized monitoring techniques. Distributed Acoustic Sensing (DAS) uses fiber optic cables to detect acoustic signals generated by $CO_2$ movement within the reservoir.

When $CO_2$ is injected, it generates acoustic waves that are captured by the fiber optic cables, which act as sensors along their entire length. DAS technology provides high-resolution, real-time data on $CO_2$ flow and reservoir conditions. It can cover extensive areas with minimal physical infrastructure, offering detailed insights into the behavior of $CO_2$ in the subsurface. This technology is particularly useful for monitoring the integrity of injection wells and detecting early signs of leakage. Chemical tracers (Igbinenikaro, 2024) involve injecting small quantities of detectable chemicals along with $CO_2$.

These tracers have distinct signatures that can be identified and measured even at low concentrations, allowing for precise tracking of $CO_2$ movement (Esho et al.., 2024). The use of chemical tracers enables highly accurate tracking of $CO_2$ migration within the reservoir. If $CO_2$ begins to move outside the intended storage area, the tracers can be detected at monitoring wells or surface stations, providing early warning of potential leaks. This method enhances the reliability of monitoring systems and supports timely interventions to address any issues (Esho et al., 2024).

Groundwater monitoring involves the use of dedicated monitoring wells to regularly sample and analyze groundwater chemistry around the $CO_2$ storage site. By measuring the concentrations of $CO_2$ and other chemical indicators in groundwater, this method can detect any migration of $CO_2$ from the storage reservoir into underground water sources.

Groundwater monitoring is critical for protecting water resources and ensuring public safety. Detecting changes in groundwater chemistry early can prevent potential contamination and allow for prompt remedial actions (Joeland and Oguanobi, 2024)).

This method provides an additional layer of security for CCS projects, enhancing public confidence in the safety and environmental integrity of $CO_2$ storage operations. Effective monitoring is essential for the safety and success of CCS projects. Recent advancements in seismic monitoring, satellite technology, distributed acoustic sensing, chemical tracers, and groundwater monitoring have significantly improved the ability to monitor CO2 storage sites. These technologies provide high-resolution, real-time data, ensuring the integrity of storage sites and enabling early detection of potential leaks (Oguanobi and Joel, 2024).

By leveraging these advanced monitoring techniques, CCS projects can achieve greater safety, efficiency, and public confidence, playing a crucial role in mitigating climate change.

## 5. Challenges and Future Directions

Implementing advanced technologies in Carbon Capture and Storage (CCS) projects faces several significant challenges (Ibigbami et al., 2024). These challenges can be broadly categorized into technical and economic considerations. The technical challenges of CCS projects revolve around the complexity and reliability of the advanced technologies required for effective CO2 injection and monitoring. High-resolution seismic imaging, satellite monitoring, distributed acoustic sensing (DAS), and chemical tracers all require sophisticated equipment and precise calibration to function correctly.

Ensuring the integrity of the data collected from these technologies is critical, as inaccuracies can lead to misinterpretation of the $CO_2$ plume's behavior and potential leakage points. Moreover, integrating these various monitoring technologies into a cohesive system that provides real-time, actionable data is complex. The interoperability of different monitoring systems, the processing and storage of vast amounts of data, and the development of algorithms for real-time analysis are ongoing technical hurdles. Additionally, maintaining the durability and functionality of sensors and other monitoring equipment in harsh subsurface conditions is a persistent challenge (Musonda et al., 2024).

Economically, the deployment of advanced CCS technologies is a significant investment. The high initial costs of installing sophisticated monitoring systems, coupled with the ongoing operational expenses for maintenance and data analysis, can be prohibitive. These costs can deter investment, particularly in regions where economic resources are limited or where the perceived financial returns on CCS projects are low. Furthermore, the economic feasibility of CCS projects is closely tied to regulatory frameworks and carbon pricing mechanisms (Faloci, 2024).

Without adequate financial incentives or penalties for carbon emissions, the cost of implementing CCS technologies may outweigh the benefits for many industries. This economic barrier can slow the adoption of advanced technologies necessary for effective and safe $CO_2$ storage. To overcome these challenges, future research and development must focus on several key areas. Reducing the costs associated with advanced CCS technologies is crucial. Research should aim to develop more cost-effective monitoring solutions, potentially through the miniaturization of sensors, advancements in materials science, and economies of scale.

Additionally, standardizing technology and processes across the industry can reduce costs by creating a larger market for CCS-specific equipment and services (Additionally, standardizing technology and processes across the industry can reduce costs by creating a larger market for CCS-specific equipment and services. 2024). Innovative approaches to real-time data analysis are essential for improving the efficiency and reliability of CCS monitoring systems. This includes the development of advanced algorithms and machine learning techniques capable of processing large datasets quickly and accurately (Ukoba and Jen, 2022, Sanni et al., 2022). Enhanced data analytics can improve the interpretation of monitoring data, providing more precise insights into $CO_2$ plume dynamics and potential leakage risks.

Furthermore, integrating artificial intelligence (AI) into monitoring systems can enable predictive analytics, allowing for proactive management of $CO_2$ storage sites (Ukoba et al., 2024). AI-driven models can simulate various scenarios, helping to optimize injection strategies and anticipate potential issues before they arise. Collaboration between industry and academia is vital for driving innovation in CCS technologies. Academic institutions can provide the research expertise and theoretical foundation necessary for developing new technologies, while industry partners can offer practical insights and testing environments (Funke et al., 2024).

Joint research initiatives and partnerships can accelerate the development and deployment of advanced monitoring technologies (Onwuka and Adu, 2024). Moreover, such collaborations can facilitate the transfer of knowledge and skills, ensuring that new technologies are effectively implemented in real-world settings. Academic programs focused on CCS technology and management can help build a skilled workforce capable of addressing the technical and operational challenges of CCS projects (Barbhuiya, 2024).

### *Recommendations*

Carbon Capture and Storage (CCS) is crucial for mitigating climate change by reducing greenhouse gas emissions. To enhance the effectiveness and adoption of CCS technologies several strategic recommendations can be made addressing current challenges and promoting future advancements. To overcome technical barriers significant investment in research and development (R&D) is essential. Governments' private sector companies and international organizations should allocate funds specifically for developing more efficient cost-effective and reliable CCS technologies.

This includes improving $CO_2$ capture processes advancing injection techniques and developing innovative monitoring systems. A robust R&D pipeline will drive technological breakthroughs reduce costs and enhance the scalability of CCS projects. Enhancing Technology Affordability and Accessibility, Making CCS technologies more affordable and accessible is critical for widespread adoption. This can be achieved through several approaches. Standardization developing industry-wide standards for CCS technologies can lower costs by promoting mass production and reducing customization.

Subsidies and Incentives Governments should offer subsidies tax incentives and grants to lower the financial barriers for companies investing in CCS. Public-Private Partnerships Collaborative projects between public entities and private companies can share the financial burden and accelerate the deployment of CCS technologies. Effective monitoring and verification are crucial for ensuring the safety and reliability of CCS projects. Recommendations include, Real-time Data Analytics Invest in AI and machine learning to enhance real-time data processing and interpretation.

These technologies can predict potential issues optimize injection processes and provide early warnings of leaks. Integrated Monitoring Systems Develop comprehensive monitoring systems that combine various technologies such as seismic monitoring satellite imaging distributed acoustic sensing (DAS) and chemical tracers to provide a holistic view of the $CO_2$ storage site. Durable Sensors Research and develop more robust sensors capable of withstanding harsh subsurface conditions to ensure long-term monitoring reliability.

Robust regulatory frameworks are necessary to ensure the safe and effective implementation of CCS projects. Recommendations for policymakers include. Clear Guidelines and Standards Develop and enforce clear guidelines and standards for all aspects of C.CS from site selection and $CO_2$ injection to monitoring and decommissioning. Carbon Pricing Mechanisms Implement carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems to make CCS economically viable and incentivize companies to reduce emissions.

Regular Inspections and Reporting Establish protocols for regular inspections and mandatory reporting of CCS activities to ensure compliance with safety and environmental standards. Collaboration between various stakeholders including industry academia governments and non-governmental organizations is essential for the advancement of CCS technologies. Recommendations include, Joint Research Initiatives Encourage joint research initiatives and consortia to pool resources share knowledge and drive innovation.

Conferences and Workshops Organize and participate in conferences workshops and seminars focused on CCS to facilitate the exchange of ideas and best practices. Educational Programs Develop educational programs and training courses to build a skilled workforce capable of implementing and managing CCS projects effectively. Gaining public support and trust is vital for the success of CCS projects. Recommendations include, Transparent Communication Provide transparent and accessible information about CCS technologies their benefits and potential risks.

Community Involvement Engage local communities in the planning and implementation of CCS projects to address their concerns and incorporate their feedback. Public Education Campaigns Launch public education campaigns to raise awareness about the importance of CCS in mitigating climate change and promoting sustainable practices.

## 6. Conclusion

Recent advancements in $CO_2$ injection and monitoring technologies have significantly improved the efficiency and safety of Carbon Capture and Storage (CCS) projects. Key developments include the use of supercritical $CO_2$ for injection, which enhances penetration and storage capacity due to its higher density and lower viscosity. Intelligent injection systems, employing sensors and data analytics, allow real-time monitoring and adjustment, optimizing injection processes and preventing potential issues. Additionally, the introduction of foamed $CO_2$ improves sweep efficiency and ensures more uniform distribution within reservoirs. On the monitoring front, technologies such as time-lapse (4D) seismic monitoring, satellite imaging, distributed acoustic sensing (DAS), and chemical tracers have revolutionized the way $CO_2$ storage sites are observed and managed. These advancements provide high-resolution, real-time data, enabling early detection of potential leaks and better understanding of $CO_2$ plume dynamics. These technologies collectively enhance the reliability and safety of CCS operations, ensuring that $CO_2$ remains securely stored. Continuous technological development is crucial for the success of CCS projects. As the global demand for effective carbon reduction strategies grows, the need for more efficient, cost-effective, and reliable CCS technologies becomes increasingly important. Ongoing research and innovation are essential to address existing challenges, such as reducing costs, improving real-time data analysis, and ensuring the long-term integrity of storage sites. Continuous development also facilitates the scalability of CCS projects, making them more accessible and economically viable for widespread adoption. Furthermore, advancements in CCS technologies contribute to building public trust and regulatory support by demonstrating the safety and effectiveness of $CO_2$ storage. They also help in meeting stringent environmental standards and achieving climate goals. Without continuous improvement and adaptation, CCS projects may struggle to keep pace with evolving environmental and economic requirements. Carbon Capture and Storage is a pivotal technology in the global effort to combat climate change. It offers a viable solution for reducing emissions from industrial sources and energy production, complementing renewable energy efforts and other carbon reduction strategies. The advancements in $CO_2$ injection and monitoring technologies play a critical role in enhancing the efficiency, safety, and economic feasibility of CCS projects, making them a more attractive option for mitigating greenhouse gas emissions. As climate change continues to pose an existential threat, the role of CCS will likely expand, necessitating further innovations and investments. The synergy between continuous technological development and robust regulatory frameworks will be essential in realizing the full potential of CCS. Ultimately, the success of CCS projects will contribute significantly to achieving global carbon neutrality and securing a sustainable future for the planet.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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