OPEN ACCESS

GRS Journal of Multidisciplinary Research and Studies
Abbriviate Tittle- GRS J Mul Res Stud
ISSN (Online)- 3049-0561
https://grspublisher.com/journal-details/GRSJ
Vol-2, Iss-3 (Mar- 2025)

ADSORPTION FOR CARBON SEQUESTRATION – A CONCISE REVIEW

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Received: 20.02.2025 **Accepted: 01.03.2025** **Published: 08.03.2025**

Abstract: The increasing concentration of carbon dioxide (CO_2) in the atmosphere due to human activities is a major contributor to global climate change. As a result, effective carbon sequestration strategies are crucial for mitigating the impacts of climate change. Among various techniques, adsorption has emerged as a promising method for CO_2 capture and sequestration. This review provides a comprehensive overview of adsorption-based technologies for carbon sequestration, focusing on the materials used, adsorption mechanisms, and key parameters influencing performance. Adsorbents such as activated carbon, metal-organic frameworks (MOFs), zeolites, and biochar are examined for their efficiency, capacity, and regeneration capabilities. Additionally, the environmental and economic aspects of these materials are discussed in the context of their practical application. The review highlights the advantages and challenges associated with adsorption processes, offering insights into potential advancements and future directions for improving the efficiency of carbon sequestration.

Keywords: *Carbon sequestration, Adsorption, CO_2 capture, Adsorbents, Environmental sustainability*.

Introduction

Carbon capture, utilization, sequestration, and storage (CCUS) is a suite of technologies designed to reduce the amount of carbon dioxide (CO_2) emitted into the atmosphere, thereby mitigating the impacts of climate change (Figure 1). These technologies are primarily aimed at capturing CO_2 from industrial processes or power generation sources before it reaches the atmosphere [1]. The captured CO_2 can then be utilized in various ways, or permanently stored underground to prevent its release [2]. Carbon capture refers to the process of capturing CO_2 from exhaust gases produced by industrial facilities, power plants, and other sources of emissions. It involves different techniques such as post-combustion capture, pre-combustion capture, and oxy-fuel combustion [3]. The captured CO_2 is then compressed and transported for further utilization or storage [4]. Carbon utilization focuses on finding innovative ways to repurpose CO_2 for industrial applications. This include converting CO_2 into valuable products like chemicals, fuels, and building materials [5]. Carbon utilization helps create a circular economy where CO_2 is treated as a resource, thus reducing emissions while creating new economic opportunities [6]

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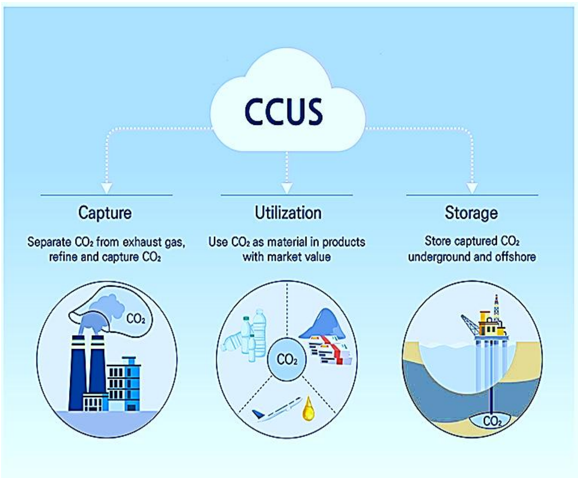

Figure 1. *Carbon capture, utilization, and storage*

Carbon sequestration involves the long-term storage of CO_2 in geological formations such as deep saline aquifers, depleted oil and gas reservoirs, or other underground rock formations. This process ensures that CO_2 is safely stored for centuries or longer, effectively preventing its release back into the atmosphere and contributing to long-term climate change mitigation [7]. Carbon storage is a key element of the broader CCUS strategy and refers specifically to the physical containment of CO_2 in underground geological formations [8]. Storage sites must be carefully selected to ensure they are capable of securely containing CO_2 without leakage [9]. Effective storage requires ongoing monitoring to ensure the integrity of the stored CO_2 and minimize the risk of environmental harm [9]. In short, CCUS is a critical component of global efforts to reduce greenhouse gas emissions and combat climate change. While significant progress has been made in developing and deploying these technologies, ongoing research, investment, and policy support are needed to make CCUS a widespread solution for large-scale emissions reduction.

Despite the significant progress in CO_2 sequestration technologies, there is a lack of comprehensive understanding regarding the comparative performance of various adsorbent materials under real-world conditions. Many studies focus on individual materials, but few offer a comparative analysis that integrates the environmental, economic, and practical application challenges [10-12]. Additionally, there is limited research on the long-term sustainability and regeneration efficiency of these adsorbents, as well as how they perform in large-scale industrial applications. There is also a need for better integration of adsorption technology with other carbon capture strategies to enhance overall effectiveness and reduce costs.

METHODS FOR CCUS

The main methods for CCUS are adsorption, absorption, membrane and cryogenic separations (Figure 2).

Figure 2. *Methods for CCUS*

Adsorption:

Adsorption involves the attachment of CO_2 molecules onto the surface of solid adsorbents like activated carbon, zeolites, or metal-organic frameworks (MOFs) (Figure 3). The CO_2 is later desorbed through changes in temperature or pressure for storage or utilization [13]. Adsorption is a versatile and energy-efficient process, especially for applications where compact, modular systems are needed. Adsorbents often have high surface areas and can be tailored for high CO_2 selectivity [14]. The process also allows for relatively straightforward regeneration of adsorbents. Adsorption systems often face limitations in terms of capture capacity and regeneration efficiency [15]. The process can be sensitive to fluctuations in temperature and pressure, which may increase operational complexity. Moreover, adsorbent material costs and stability over extended cycles need improvement.

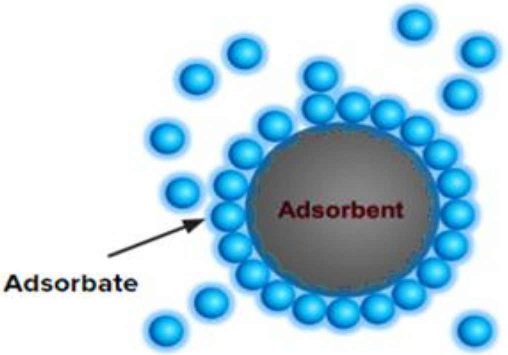

Figure 3. *Adsorption mechanism for CCUS*

Absorption:

Absorption is a key unit operation in carbon capture, where CO_2 is absorbed into a liquid solvent, typically amine-based solutions (Figure 4). The process occurs in an absorber column, where CO_2-rich flue gas comes into contact with the solvent, resulting in CO_2 being dissolved [16]. Absorption is a mature and well-established technology, particularly effective in post-combustion carbon capture from flue gases. It offers high CO_2 capture efficiency and can be optimized for specific CO_2 concentrations [17]. Additionally, solvents can be regenerated and reused, reducing long-term operational costs. The process is energy-intensive due to the need for solvent regeneration, often requiring significant thermal energy. This leads to higher operating costs and can reduce the overall efficiency of power plants [18]. The potential for solvent degradation and the environmental concerns around solvent disposal are additional challenges.

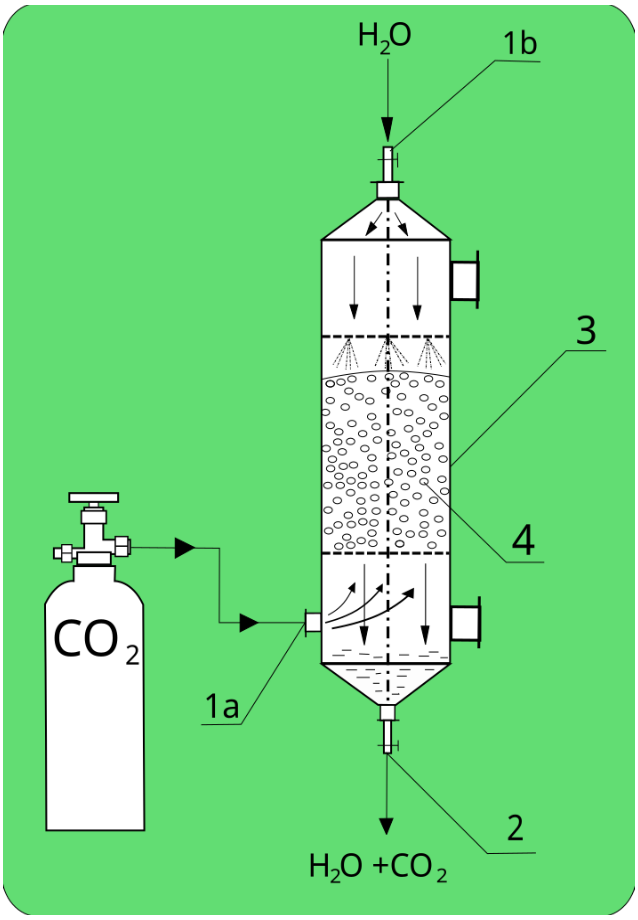

Figure 4. *Laboratory absorber. 1a): CO2 inlet; 1b): H2O inlet; 2): outlet 3): absorption column; 4): packing.*

Membrane separation

Membrane separation involves passing CO_2-rich gas through a semi-permeable membrane that selectively allows CO_2 to pass through while retaining other gases. This technique can be used in both pre- and post-combustion CO_2 capture [19]. Membranes are typically less energy-intensive than other separation methods and can be compact and modular. They have low operational costs and require minimal chemical inputs. Membrane systems can also be easily integrated into existing infrastructure. Membranes often have limitations in terms of selectivity and permeability, which can reduce their overall effectiveness in capturing CO_2 from complex gas mixtures [20]. Additionally, membrane fouling and degradation over time can affect performance, leading to increased maintenance and operational costs.

Cryogenic separation

Cryogenic separation involves cooling the CO_2-containing gas stream to very low temperatures, causing CO_2 to condense into a liquid, which can then be separated. This process is effective for both pre- and post-combustion CO_2 capture [21]. Cryogenic separation can be highly effective in achieving high purity CO_2 capture, especially in situations where the CO_2 concentration is high. It can also be integrated with other processes, such as natural gas processing, to provide dual benefits. The process is energy-intensive, requiring significant refrigeration and energy input to cool the gas to the necessary temperatures. This can result in higher operational costs [22]. Additionally, the complexity of cryogenic equipment and the need for specialized infrastructure can limit its widespread application.

In summary, unit operations such as absorption, adsorption, membrane separation, and cryogenic separation offer distinct advantages and challenges. While these technologies are essential for effective CCUS, their efficiency and scalability depend on overcoming technical, economic, and regulatory barriers.

ADSORPTION FOR CCUS

Adsorption is a promising technology for Carbon Capture, Utilization, and Storage (CCUS), where carbon dioxide (CO_2) is captured by solid adsorbent materials, typically through physical or chemical interactions [14]. In this process, CO_2 molecules are attracted to and bound on the surface of an adsorbent material, such as activated carbon, zeolites, metal-organic frameworks (MOFs), or biochar. Adsorption can occur at either high or low pressures, depending on the type of adsorbent and the specific conditions of the gas mixture. After the adsorption step, CO_2 can be desorbed by lowering the pressure or raising the temperature, making the process reversible and allowing for the regeneration of the adsorbent material for repeated use.

The main advantages of adsorption for CCUS include its versatility, high CO_2 selectivity, and relatively low energy consumption compared to other CO_2 capture methods like absorption. Adsorption is also scalable, making it suitable for both small and large-scale applications [15]. Additionally, advanced adsorbents such as MOFs offer tunable properties, enabling optimization for specific CO_2 concentrations and conditions. However, there are challenges associated with adsorption-based CO_2 capture. One key issue is the relatively lower CO_2 capture capacity of many adsorbents compared to liquids in absorption processes. The energy required for the regeneration of the adsorbent can also be substantial, particularly for materials with low thermal conductivity or limited stability [13]. Additionally, the cost of high-performance adsorbents and their long-term durability remain critical concerns. Despite these challenges, ongoing research in material science and process optimization continues to enhance the effectiveness of adsorption for large-scale CO_2 capture, making it a promising candidate for CCUS technologies

ADSORBENTS FOR CCUS

Adsorbents play a central role in carbon capture, utilization, and storage (CCUS) by selectively trapping CO_2 from flue gases or other emission sources [23]. The effectiveness of an adsorbent depends on its surface area, pore structure, chemical composition, and affinity for CO_2 (Figure 5). Various types of adsorbents are used for this purpose, each with distinct properties that make them suitable for specific applications in CCUS.

Activated carbon is one of the most widely used adsorbents due to its high surface area and porosity, which provide ample space for CO_2 molecules to attach [24]. Activated carbon is particularly effective in capturing CO_2 at low concentrations and is also relatively inexpensive. However, its capacity to adsorb CO_2 is limited compared to more advanced materials, and its regeneration efficiency can be low, making it less suitable for large-scale, long-term use in some applications.

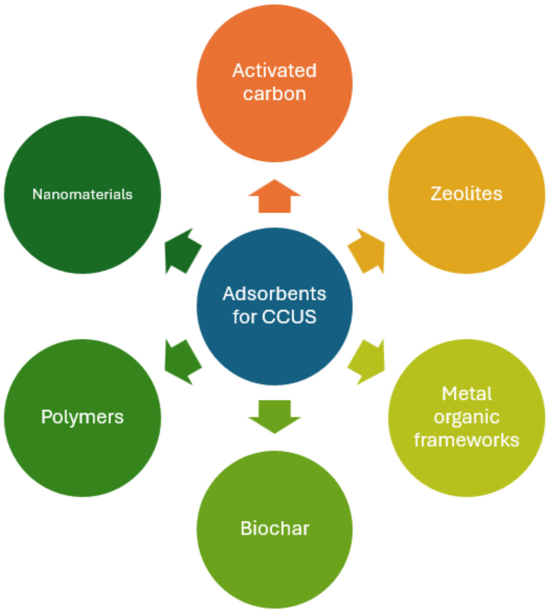

Figure 5. *Adsorbents for CCUS*

Zeolites are microporous materials that have a well-defined crystalline structure, which provides selective adsorption of CO_2 molecules. Due to their high thermal stability, zeolites are particularly suited for high-temperature applications. They are capable of high CO_2 adsorption capacity and can be regenerated with lower energy input. However, their adsorption capacity can be sensitive to moisture and other contaminants, which can reduce their efficiency in certain environments [25].

Metal-Organic Frameworks (MOFs) represent a cutting-edge class of adsorbents that are gaining significant attention for CO_2 capture. MOFs are highly porous, with customizable structures that allow for tunable surface areas and chemistries, which can be optimized for CO_2 selectivity. Their large internal surface area and ability to adsorb CO_2 at both low and high pressures make them highly efficient. However, MOFs are still relatively expensive and can suffer from issues related to stability and scalability, which limit their widespread commercial adoption [26].

Biochar, a carbon-rich material produced by the pyrolysis of organic biomass, is an emerging adsorbent in the field of CCUS [27]. Biochar is particularly attractive due to its sustainability, low cost, and potential for large-scale production from waste biomass. It has moderate CO_2 adsorption capacity and can be tailored for improved performance through surface modifications. However, its CO_2 capture efficiency is generally lower than that of activated carbon or zeolites, and its regeneration can be more challenging due to its complex pore structure.

Polymeric Adsorbents are another class of materials that have shown potential for CO_2 capture. These materials can be designed to have high selectivity for CO_2 and are typically more cost-effective than inorganic adsorbents like zeolites and MOFs. Their lower thermal stability and susceptibility to degradation under harsh conditions, however, can limit their long-term applicability in CCUS [28].

Nanosorbents represent a new and exciting class of materials for carbon capture, utilization, and storage (CCUS). These materials are typically nanostructured adsorbents, which include nanoparticles, nanocomposites, and materials engineered at the nanometer scale [29]. The unique properties of nanosorbents, such as their extremely high surface area, tunable surface chemistry, and enhanced reactivity, make them particularly promising for CO_2 capture applications.

In summary, the choice of adsorbent for CCUS depends on factors like CO_2 capture efficiency, regeneration energy requirements, cost, and material stability. While advanced materials like MOFs show great potential, more traditional adsorbents like activated carbon and zeolites remain popular due to their proven effectiveness and lower costs. Ongoing research and development are focused on enhancing the performance, stability, and scalability of these adsorbents to make them more viable for large-scale carbon capture applications.

ADSORPTION MECHANISMS FOR CCUS

Adsorption is a critical technology in CCUS, and understanding its various mechanisms is essential for improving efficiency and scalability. The following sections explore the key concepts involved in adsorption processes for CO_2 capture, including adsorption hysteresis, isotherms, kinetics, mass transfer, thermodynamics, and continuous adsorption (Figure 6).

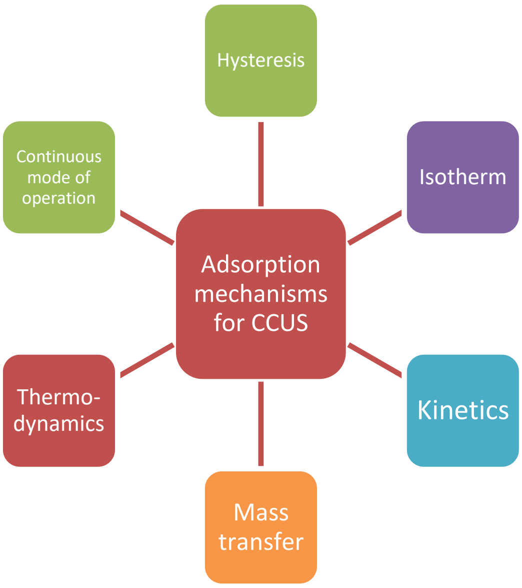

Figure 6. *Adsorption mechanisms for CCUS*

Adsorption hysteresis in CCUS

Adsorption hysteresis refers to the phenomenon where the adsorption and desorption processes exhibit different behaviors under identical conditions. This is often observed in porous materials, where CO_2 molecules adsorbed on the surface do not desorb in the same manner [30]. The hysteresis loop typically arises due to the energy barriers in the pore structure, as the adsorbate may not easily desorb when the external conditions (e.g., pressure or temperature) are reversed. In the context of CCUS, hysteresis can impact the efficiency of the desorption process, requiring more energy for complete regeneration of the adsorbent. Minimizing hysteresis is essential for optimizing the overall performance and reducing energy costs associated with CO_2 capture and storage.

Adsorption isotherms in CCUS

Adsorption isotherms describe the relationship between the amount of CO_2 adsorbed and its partial pressure or concentration at constant temperature [31]. The most used isotherms in CCUS studies are the Langmuir and Freundlich isotherms. The Langmuir isotherm assumes a monolayer adsorption with uniform binding sites, suggesting that once an adsorption site is filled, no further CO_2 molecules can be adsorbed. The Freundlich isotherm, on the other hand, allows for non-uniform adsorption sites and is more suitable for systems with heterogeneous surface structures. These isotherms provide valuable insights into the adsorption capacity and efficiency of materials, helping to guide the selection of adsorbents for CO_2 capture processes in CCUS applications.

Kinetics of adsorption in CCUS

The kinetics of adsorption refer to the rate at which CO_2 molecules are adsorbed onto the surface of an adsorbent. In CCUS, understanding adsorption kinetics is crucial for optimizing the contact time between the adsorbent and CO_2 in real-world applications. The adsorption process typically follows a two-step mechanism: an initial rapid phase, followed by a slower phase as the adsorption sites become occupied [32]. Models such as the pseudo-first-order and pseudo-second-order kinetic models are commonly used to describe the adsorption rate. The choice of adsorbent, temperature, pressure, and CO_2 concentration all influence the kinetics. Faster adsorption rates are desirable in large-scale applications to increase throughput and reduce the overall cost of CO_2 capture.

Mass transfer in adsorption for CCUS

Mass transfer plays a significant role in the efficiency of the adsorption process. It refers to the movement of CO_2 molecules from the bulk phase to the adsorbent surface, where adsorption occurs. Effective mass transfer requires the adsorbent to have a large surface area and a well-developed pore structure to allow for rapid diffusion of CO_2 molecules. The mass transfer rate is governed by the diffusion of CO_2 through the gas phase, the boundary layer near the adsorbent surface, and the pores of the adsorbent [33]. Poor mass transfer can limit the efficiency of the adsorption process, particularly in larger-scale systems where high flow rates of CO_2 are encountered. Optimizing the adsorbent's pore structure and selecting materials with appropriate diffusion properties can help enhance the mass transfer and overall performance of the adsorption system.

Thermodynamics of adsorption in CCUS

The thermodynamics of adsorption govern energy changes during the process. The adsorption of CO_2 is typically exothermic, meaning that it releases heat, which can influence the overall energy balance of the system. Adsorption capacity and the equilibrium state are also influenced by temperature and pressure, which dictate the distribution of CO_2 molecules between the adsorbent surface and the gas phase. Understanding these thermodynamic principles helps in designing adsorption systems that can operate efficiently under varying conditions [34]. In addition, the Gibbs free energy change (ΔG) for the adsorption process provides insight into whether the adsorption is spontaneous. The thermodynamic properties also guide the selection of regeneration conditions, where the adsorbent is heated or depressurized to release the adsorbed CO_2.

Continuous adsorption for CCUS

In continuous adsorption, CO_2 is captured in a continuous flow of gas through a bed of adsorbent, as opposed to batch processes that operate in cycles. This method is particularly useful for large-scale CO_2 capture applications, as it allows for constant operation without the need for frequent shutdowns [34]. Continuous adsorption systems, such as fixed-bed or fluidized-bed reactors, provide a steady throughput of CO_2, improving overall efficiency. In these systems, the adsorbent can be periodically regenerated through processes like temperature or pressure swing adsorption (TSA or PSA), ensuring continuous CO_2 capture and minimizing downtime. However, challenges like pressure drop, channeling, and uneven adsorption front propagation must be addressed for effective design and operation. Continuous adsorption offers a scalable solution for CCUS, providing high throughput while maintaining long-term operational stability.

In summary, adsorption is a crucial process for CO_2 capture in CCUS, and understanding the underlying principles—such as adsorption hysteresis, isotherms, kinetics, mass transfer, thermodynamics, and continuous adsorption—enables the design of more efficient and scalable systems. Optimizing these factors is key to improving the energy efficiency, capacity, and overall performance of adsorption-based CO_2 capture technologies. By continuing to advance the understanding of these processes and developing better adsorbent materials, adsorption can become a central tool in reducing CO_2 emissions and achieving global sustainability goals.

CHALLENGES AND FUTURE DIRECTIONS IN ADSORPTION FOR CCUS

Challenges

Adsorbent capacity and selectivity:

- Many adsorbents exhibit limited CO_2 capture capacity, especially under low CO_2 concentrations.

- Achieving high selectivity for CO_2 over other gases (e.g., nitrogen or oxygen) in mixed gas streams remains challenging.

Energy intensity of regeneration:

- Regenerating adsorbents often requires significant amounts of energy, particularly for materials that exhibit high hysteresis or low thermal conductivity.

Adsorbent stability and durability:

- Adsorbents, especially those that are chemically modified (e.g., MOFs or amine-based materials), may degrade over time, reducing their efficiency and lifespan.

Cost of* adsorbents*:

- High-performance adsorbents, such as metal-organic frameworks (MOFs) and carbon nanotubes (CNTs), are expensive to synthesize and may not be cost-effective for large-scale CO_2 capture.

Mass transfer limitations:

- Poor mass transfer due to low diffusion rates in some adsorbent materials can limit the overall efficiency of the adsorption process, especially at large scale or high CO_2 flow rates.

Regulatory and environmental concerns:

- The environmental impact of producing and disposing of adsorbents, particularly nanomaterials, must be considered to ensure the sustainability of CCUS technologies.

Future directions

Development of advanced adsorbents:

- Design and synthesis of new materials with higher CO_2 adsorption capacities, such as novel MOFs, carbon-based nanomaterials, and hybrid composites.
- Focus on developing low-cost, scalable adsorbents that maintain high efficiency over multiple adsorption-desorption cycles.

Improved regeneration techniques:

- Research into energy-efficient regeneration methods, such as using lower temperatures or pressure swing adsorption (PSA), to reduce the overall energy consumption of the system.

Nanotechnology and nanomaterials:

- Incorporating nanomaterials, such as graphene and carbon nanotubes, to enhance the surface area and adsorption kinetics of adsorbents.

- Investigation into the potential of nanosorbents for improving CO_2 selectivity and efficiency in challenging conditions (e.g., high humidity or fluctuating temperatures).

Integration with renewable energy:

- Integration of CCUS processes with renewable energy sources (e.g., solar or wind) to power the regeneration step and reduce the carbon footprint of CO_2 capture systems.

Scale-up and commercialization:

- Focus on scaling up adsorption technologies from laboratory and pilot-scale to industrial-scale applications, ensuring economic feasibility and practical deployment.

Hybrid systems and process optimization:

- Exploring hybrid systems combining adsorption with other CO_2 capture technologies (e.g., absorption, membrane separation) to optimize performance and reduce energy consumption.

Automation and smart monitoring:

- Implementing automation and real-time monitoring systems to optimize adsorption performance and monitor adsorbent conditions, improving system efficiency and reducing maintenance.

These future directions will help overcome the current challenges and make adsorption a more viable and cost-effective method for large-scale CO_2 capture in CCUS technologies

CONCLUSION

In conclusion, adsorption remains a promising and versatile method for carbon sequestration, offering several advantages such as high selectivity, fast kinetics, and potential for regeneration. Among the various adsorbents, materials such as activated carbon, MOFs, and biochar show great potential due to their high surface area, tunable properties, and sustainability. However, challenges such as adsorbent stability, regeneration efficiency, and cost-effectiveness need to be addressed for large-scale implementation. Ongoing research into developing new materials and improving the adsorption process is crucial for enhancing the efficiency of carbon capture and storage technologies. As the global need for climate change mitigation intensifies, adsorption-based carbon sequestration could play a significant role in reducing atmospheric CO_2 concentrations and helping achieve sustainability goals.

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