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Research article

Advancements and Challenges in Polymer-Based Adsorbents for Carbon dioxide (CO_2) Capture

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Abstract

Carbon capture and storage (CCS) is a critical strategy for mitigating carbon dioxide emissions and the negative effects of climate change. Among various CCS technologies, adsorption has emerged as a promising approach due to its low energy consumption, ease of operation, and versatility. In recent years, polymer materials have gained increasing attention for use as adsorbents due to their tuneable properties and high carbon capture capacities. This review paper presents an overview of the technical and sustainable developments in the field of polymer materials and technology for carbon capture using adsorption. This review focuses on the types of polymer materials that have been investigated for carbon capture applications, including synthetic and natural polymers, as well as their composites. The second part discusses the adsorption performance of polymer materials for capturing carbon dioxide, including their adsorption capacity, selectivity, and regeneration properties. Finally, the review discusses the sustainability aspects of using polymer materials for carbon capture, including their environmental impact and cost-effectiveness. The review concludes that polymer-based adsorbents have shown great potential for carbon capture applications, and further research and development are needed to optimize their performance and make them economically viable.

Keywords: Carbon capture, adsorption, polymers, sustainable developments

1. Introduction

Carbon dioxide (CO_2) emissions play a major factor in global warming. According to an international report by the Global Carbon Project (Friedlingstein et al., 2022), atmospheric CO_2 concentrations are projected to reach an average of 417.2 parts per million in 2022. This is despite the reduction in global carbon emissions by 5.1% due to COVID-19, as rapid recovery led to an emission rate of 36.3 Gt in 2021 (Al-Absi et al., 2023). One of the primary reasons for this increase in atmospheric CO_2 is the use of fossil fuels to generate energy (Hassan et al., 2022). This has severe consequences such as a) rising global temperatures, b) rise in sea level due to melting of glaciers, c) increase in the acidification of the ocean, causing consequent damage to the marine ecosystem, and d) unfavourable climatic changes and disasters. Although alternative energy resources are being explored to meet energy requirements, the use of fossil fuels to meet most of the global energy needs cannot be ignored (Connolly et al., 2020). Therefore, the scientific community is actively engaged in research and development to check the increase in concentration of atmospheric CO_2 by capturing it at the source. Capturing CO_2 at the massive quantities recorded would require resources and technologies that can operate economically at a large multi-gigaton scale, which we currently lack (Gür, 2022a). CO_2 capture is an expensive and highly energy-intensive process with a lot of

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logistics involved, and the diversity of the emission sources varies due to factors such as volume, composition, location, type, and industry sector. This highlights the need for a multiprong strategy that emphasizes the necessity to develop a wide range of technologies, materials, and processes for carbon capture. Accordingly, carbon capture and storage (CCS) has emerged as a promising technology for mitigating greenhouse gas emissions. The current mainstream CO_2 capture technology is divided into pre-combustion capture, post-combustion capture, and oxyfuel capture. Each of these technologies presents unique challenges including energy-intensive processes, scale-up difficulties, poor efficiencies, low stability, low capacity, and high capital investment costs (Kanjilal et al., 2020). A comparison of the four technologies is given below in Table 1, highlighting the trend in recent studies conducted in the field. Briefly, the three may be described as (Sattari et al., 2021a). Figure 1 illustrates carbon capture and storage techniques.

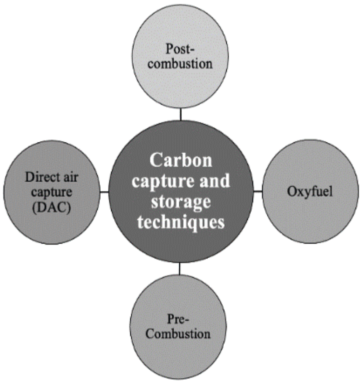

Figure 1: Carbon capture and storage techniques

- Pre-combustion: CO_2 is captured from partial sources such as incomplete combusted syngas, where the CO_2 concentration is between 15% and 50% (Figueroa et al., 2008).
- Post-combustion: CO_2 is captured from flue gas containing nearly 5–15% CO_2 after complete fuel combustion (Kenarsari et al., 2013a).
- Oxyfuel capture: CO_2 is captured from gases obtained through combustion undergone with pure oxygen instead of air (Zhu et al., 2021).
- Direct air capture (DAC): Extraction of carbon dioxide (CO_2) directly from ambient air. It typically employs a chemical process or a sorbent material to capture CO_2 molecules from the atmosphere (Keith et al., 2018).

Carbon capture technology is also important in realizing the potential uses of carbon dioxide as a raw material. CO_2 can be used to make certain chemicals, at least in the short term (Poliakoff et al., 2015), as a solvent to extract supercritical fluid, vasodilating agent, as aesthetic, food packaging gas, as food propellant, as a production of ethanol, as a fertilizer, and soil sequestering agent, etc (Vaz et al., 2022), (Gonzalez-Diaz et al., 2020).

Table 1 Comparison of mainstream carbon capture and storage techniques

Technology	Advantages	Disadvantages	References
• Pre-combustion	• Relatively less energy-intensive process • Consumes relatively less water • May generate syngas as an alternate fuel	• Inadequate commercial availability • High temperatures are required • This may lead to solvent degradation	• (Zhou et al., 2021)
• Post-combustion	• Can be adopted by existing plants, and applied at large-scale • Comprehensive research already exists to improve energy efficiency	• Despite existing literature, large-scale energy efficiency is lacking	• (Sreenivasulu et al., 2015), (Mukherjee et al., 2019)
• Oxyfuel	• High efficiency • Low emission of pollutants, particularly of NO_X • Purification of the CO_2 stream at the end of the process is relatively easier	• Requires specialized equipment • Is heavily dependent on effective air fractionation • High risk and safety management is needed due to oxygen requirement	• (Brigagão et al., 2019), (Brigagão et al., 2021)
• Direct air capture (DAC)	• Removes CO_2 directly from the atmosphere, regardless of its source.	• Energy-intensive process, requiring significant amounts of electricity.	• (Keith et al., 2018)

Technology	Advantages	Disadvantages	References
	• Can be deployed in various locations, including remote areas. • Offers flexibility in placement and scalability.	• High operational costs compared to other carbon capture methods.	

As CO_2 continues to be repurposed in this manner, it is important to note that climate change and energy cannot be separated from one another. CO_2 emissions from energy production have an impact on climate change, so solutions to mitigate climate change must also get along with the rising energy demands of the global community. Likewise, CCS technologies must also be more stringent in their energy requirements, as CO_2 emissions associated with their energy requirements must not cancel out the carbon capture (Lackner et al., 2012). Energy is also intimately linked with society and the environment through food and freshwater availability, in turn affecting population shifts, growth, and mass migrations (Gür, 2022b).

Polymer-based adsorbents have emerged as a promising option for CCS due to their high selectivity, tunability, and low cost compared to other types of adsorbents (such as zeolites and activated carbons) and traditional CCS technologies (such as amine-based absorption and cryogenic distillation).

One of the key advantages of polymer-based adsorbents is their ability to selectively capture CO_2 from industrial gas streams at low concentrations and high pressures, which are common in many industrial processes. Furthermore, polymer-based adsorbents can be synthesized using a variety of polymers, such as polyethyleneimine (PEI), polyvinylamine (PVAm), and polyethylenimine-grafted graphene oxide (PEI-GO), which can be tailored to optimize their performance for specific gas streams and operating conditions (Lai et al., 2021).

The use of polymer-based adsorbents in CCS also has important implications for sustainability and environmental impact. Compared to traditional CCS technologies, polymer-based adsorbents have lower energy requirements and can operate at lower temperatures, reducing the overall environmental impact of the process. Furthermore, the use of renewable polymers and green synthesis routes can further improve the sustainability of polymer-based adsorbents for CCS (Pardakhti et al., 2019).

Overall, the significance of polymer-based adsorbents in CCS lies in their potential to provide a cost-effective and sustainable solution for capturing CO_2 from industrial gas streams, while also offering opportunities for tailoring their performance and optimizing their environmental impact. Continued research and development in this area can further improve the effectiveness and sustainability of polymer-based adsorbents for CCS.

The aim of this review paper is to provide an overview of recent advancements and challenges in the development and deployment of polymer-based adsorbents for CO_2 capture. The paper focuses on the environmental impact of polymer-based adsorbents and their potential for sustainable manufacturing. In this review, we discuss various types of polymer-based adsorbents and their properties, advantages, and disadvantages for CO_2 capture. We also evaluate the environmental impact of CO_2 capture technologies, including polymer-based adsorbents, and the importance of sustainable manufacturing approaches to reduce the environmental impact of these technologies. Finally, we highlight current challenges in the development and deployment of polymer-based adsorbents and discuss potential future directions for their further research and applications in CO_2 capture.

2. Adsorption as a method of carbon dioxide capture: overview

Among the range of carbon capture techniques available, adsorption has been one of the benchmark techniques used due to its high efficiency and easy application. In the case of air or ambient carbon capture techniques, it is the only other feasible technique along with

absorption. However, adsorption still faces challenges as a carbon capture technology. A comparison of its advantages and disadvantages in comparison to other methods can be seen in Table 2 below. The adsorbed CO_2 can be recovered

by swinging the pressure (PSA) or temperature (TSA) of the system

containing the CO_2-saturated sorbent (Leung et al., 2014). The working principle of carbon capture through adsorption can thus be summarised in the following steps:

- Adsorption of CO_2 on the surface of the adsorbent material
- Diffusion of the other gases through the adsorbent to exit the system
- Desorption of CO_2 through PSA or TSA, and its storage

Table 2 Comparison of adsorption versus other carbon capture technologies

Technology	Advantages	Disadvantages	References
Absorption	• Relatively lower capital cost • Better purification rate and fast application • Usually, the option viable in the gas liquefaction industry	• High energy cost for regeneration • High transport cost post-capture • High equipment corrosion and fouling rate • The solvent used is easily degraded	(L. Zhao et al., 2014), (T. He et al., 2023), (Sreedhar, Nahar, et al., 2017)
Membranes	• Can be adopted relatively easily since it is already in use for other gases. • High separation efficiency is possible.	• High membrane manufacturing cost • Membrane fouling effect • Requirement of driving force • Need for high permeability and selectivity in membrane	(Merkel et al., 2010), (Hussain & Hägg, 2010), (Sreedhar, Vaidhiswaran, et al., 2017)
Cryogenic technology (distillation/condensation/sublimation)	• Can be applied relatively easily to existing industries • Can be used to directly obtain liquid CO_2 • Does not require high pressure	• Operating conditions needed for refrigeration have a high energy requirement • More suitable for higher carbon concentrations (>50%), and requires moisture removal • Process efficiency may be hindered due to solid carbon buildup in equipment	(Tuinier et al., 2010), (Shen et al., 2022), (Song et al., 2017)
Hydrate-based carbon capture (HBCC)	• Has large CO_2 capture and storage capacity • Can enable large-scale cyclic capture • Has tolerance to feed impurities • Consumes relatively less energy	• High pressure and low temperature are required • There may be secondary pollution of promoter • Other molecules trapped in the cage structure may	(Sun & Kang, 2016), (Nguyen et al., 2022), (M. Yang et al., 2013), (Park et al., 2013)

Technology	Advantages	Disadvantages	References
		affect the carbon capture efficiency • Studies connected to cost evaluation are scarce	
Chemical looping combustion	• High concentration of CO_2 can be obtained • The need for purification of the captured CO_2 is relatively less	• Sorbent may show decay in reactivity over cycles • High attrition rate and vulnerability • High capital cost required	(Luo et al., 2018), (Hong, 2022), (Hossain & de Lasa, 2008)
Adsorption	• May be reversible • Recycling of adsorbent is possible • Suited for a long-term process • High efficiency	• Relatively low CO_2 selectivity • Risk of sorbent degradation and attrition during the operation • Operation may be discontinuous or intermittent • Periodic regeneration or replacement of sorbent required • Pressure drops required may be high in certain applications	(Samanta et al., 2011), (Song et al., 2018), (B. Li et al., 2013)

One of the main challenges of adsorption is choosing the suitable adsorbent. The desirable CO_2 adsorption characteristics are moderate head of adsorption, high selectivity, stable cycle performance and longevity, high adsorption capacity, fast adsorption kinetics, and environmental sustainability. To this end, several materials have been investigated with varying degrees of success (Y. Li et al., 2022). Adsorbents can be made from a variety of materials, including polymers, zeolites, and activated carbons, and can be designed with specific surface properties and pore sizes to enhance their CO2 adsorption capacity. However, there are still challenges to be addressed in optimizing the efficiency and scalability of adsorption-based carbon capture systems, including improving the selectivity and durability of adsorbents and reducing the cost of the technology.

3. Advancements in Polymer-Based Adsorbents for CO_2 Capture

Polymer-based adsorbents for CO_2 capture can be categorized into various types based on their chemical structure, synthesis method, and application. The most commonly used polymer-based adsorbents are polyamines, polyamines, and polyamides (Maleki et al., 2023). Polyamines, such as polyethyleneimine (PEI) and polyallylamine (PAA), have a high affinity for CO_2 due to their amino groups, which can interact with CO_2 molecules through electrostatic interactions and hydrogen bonding (Chaikittisilp et al., 2011). Polyamines, such as polymers derived from Schiff base reactions, are also effective CO_2 adsorbents due to their imine groups, which can react with CO_2 to form stable carbamate bonds. Polyamides, such as polyacrylonitrile (PAN) and polyvinylidene fluoride (PVDF), are widely used due to their good thermal and chemical stability (Fang et al., 2020). Other types of polymer-based adsorbents include polystyrene-based adsorbents, poly (ionic liquid)s, and porous organic polymers. These materials offer a range of structural and chemical properties, making them attractive for various CO_2 capture applications (Tan & Tan, 2017).

Polymer-based adsorbents for CO_2 capture exhibit a wide range of properties and characteristics that make them attractive for different applications. These materials have a high surface area, porosity, and selectivity towards CO_2, which are essential for the effective separation of CO_2 from flue gas streams. In addition, they possess good thermal and chemical stability, which ensures their long-term durability and resistance to degradation (Dutta et al., 2014). The pore size distribution and surface chemistry of the polymer-based adsorbents can be tailored to enhance their CO_2 adsorption capacity, selectivity, and kinetics. They can be easily synthesized using a variety of methods, such as sol-gel, precipitation, and electrospinning, which allows for precise control over their structure and properties (Liu et al., 2017). Furthermore, these materials can be easily regenerated and reused, which minimizes the environmental impact and reduces the overall cost of the CO_2 capture process.

However, there are also some disadvantages to consider. Polymer-based adsorbents can be more expensive than traditional solvent-based technologies, and their long-term stability and performance under real-world conditions still need to be further studied (Kenarsari et al., 2013b). The development of efficient regeneration techniques and the need for large-scale production of these materials also remains a challenge.

Polymer-based adsorbents can be made from a variety of materials, including synthetic polymers, natural polymers, and their derivatives (Mansoori et al., 2020), which have been discussed below. In addition, some researchers have explored the use of hybrid materials, which combine different types of polymers or incorporate nanoparticles or other materials to enhance the performance of the adsorbent. The choice of polymer and other materials will depend on factors such as the desired properties of the adsorbent, the cost of production, and the availability of raw materials (Muxika et al., 2017).

3.1 Polymers from synthetic materials

Synthetic polymers, such as polyethyleneimine (PEI), polyvinylamine (PVAm), polyethyleneglycol (PEG), and polyacrylonitrile (PAN), have received considerable attention as potential adsorbents for CO_2 capture due to their high selectivity and capacity for CO_2. For instance, a recent study by Wang et al., reported the development of a high-capacity polyethylene glycol-grafted polyethylenimine sorbent for CO_2 capture (L. Wang et al., 2019). Another study by Xuezhong He, demonstrated the facile fabrication of novel polyvinylamine-based hybrid materials for high-performance CO_2 capture (X. He, 2021). PEI is one of the most extensively studied synthetic polymers for CO_2 capture, owing to its high amine density and strong interaction with CO_2 (Sanz et al., 2010). PAN has been shown to have high thermal stability and resistance to degradation (Al-Absi et al., 2022).

Despite their advantages, synthetic polymers also have some drawbacks that limit their practical use for CO2 capture. For example, the production of synthetic polymers can be energy-intensive and result in the generation of hazardous waste. Additionally, synthetic polymers can be prone to degradation and loss of activity over time, which may require frequent replacement or regeneration of the adsorbent (M. Wang et al., 2016).

In addition to their CO_2 capture performance, the sustainability of synthetic polymers is also an important consideration for their practical use. Synthetic polymers are often derived from non-renewable resources and require energy-intensive processes for their production (Mülhaupt, 2013). Furthermore, their disposal after use can contribute to environmental pollution. To address these challenges, researchers have explored various approaches to enhance the sustainability of synthetic polymers. For instance, the use of bio-based monomers, such as succinic acid and citric acid, can reduce the reliance on fossil fuels and minimize the environmental impact of polymer production (Tsivadze et al., 2021). Another approach is the development of recycling and regeneration strategies that can extend the lifespan of the polymer adsorbents and reduce the waste generated from their use (Ünveren et al., 2017).

Nevertheless, synthetic polymers remain an important class of materials for CO_2 capture, and research continues to explore methods to improve their performance and reduce their environmental impact. Further investigation of the properties and performance of these materials, as well as the development of sustainable and cost-effective production methods, could help to advance the field of polymer-based adsorbents for CO_2 capture.

3.2 Polymers from natural materials

Polymers obtained from natural materials have been observed as adsorbents for CO_2 capture due to their biodegradability, abundance, and low toxicity. These materials can be derived from a variety of sources, including plant and animal waste, and have been investigated for their CO_2 capture performance and sustainability (Yeamin et al., 2021). One example is chitosan, a biopolymer derived from chitin found in the shells of crustaceans. Chitosan has been shown to have good CO_2 capture performance and can be modified to improve its stability and selectivity (Chagas et al., 2020). For instance, chitosan-based aerogels with high surface area and pore volume have been synthesized and tested for CO_2 capture, demonstrating good selectivity and cyclic stability (Fan et al., 2021). Another example is lignin, a polymer found in plant cell walls. Lignin has been investigated as a low-cost and renewable adsorbent for CO_2 capture and can be sourced from various agricultural and forestry waste streams (B. Zhao et al., 2021). For example, a recent study reported the preparation of a lignin-based adsorbent using corn stover lignin, which exhibited high CO_2 adsorption capacity and selectivity (Guo et al., 2021). However, the use of polymers obtained from natural materials for CO_2 capture is still in its early stages, and more research is needed to optimize their performance, scalability, and sustainability. The use of polymers obtained from natural materials for CO_2 capture also presents opportunities for sustainable waste management and resource recovery (Javed et al., 2019).

3.3 Polymers from hybrid materials

Polymer-based adsorbents can also be synthesized from hybrid materials, which combine the advantages of different materials to achieve enhanced CO_2 capture performance and sustainability. One example is metal-organic frameworks (MOFs), which are porous materials composed of metal ions linked by organic ligands. MOFs have attracted attention for their high surface area and can be incorporated into polymer matrices to improve their CO_2 adsorption capacity and selectivity. For instance, a recent study reported the preparation of a MOF-polymer composite adsorbent using MIL-53 and polyvinylidene fluoride, which exhibited excellent CO_2 adsorption performance and cyclic stability (Zhang et al., 2017). Other examples of hybrid materials for polymer-based adsorbents include graphene oxide-polymer composites, zeolite-polymer composites, and silica-polymer composites. These materials have been investigated for their CO_2 capture performance and sustainability and have shown promising results (Stankovic et al., 2022; Zagho et al., 2021).

The synthesis of polymer-based adsorbents derived from hybrid materials often involves the use of solvents, which can have environmental and health impacts. To address this issue, researchers have explored the use of eco-friendly solvents such as water, ionic liquids, and deep eutectic solvents (DESs) for the synthesis of these materials. For example, a recent study reported the preparation of a zeolite-polymer composite adsorbent using a DES solvent, which exhibited high CO_2 adsorption capacity and selectivity (Ahmad et al., 2018). Additionally, efforts have been made to develop sustainable manufacturing processes for these materials, such as using renewable resources as starting materials, minimizing waste generation, and optimizing energy consumption. For instance, a recent study reported the synthesis of a chitosan-polyvinyl alcohol composite adsorbent using shrimp shells as a renewable resource, which exhibited high CO_2 adsorption capacity and selectivity and reduced environmental impact (Hameed et al., 2007).

However, the development of scalable and cost-effective synthesis routes for these hybrid materials remains a challenge, and further research is needed to optimize their performance and reduce their environmental impact. Moreover, the long-term stability and regeneration of these materials under practical conditions need to be further investigated.

4. Use of polymers in adsorption-based hybrid process of carbon capture

As seen from Table 2, standalone carbon capture technologies pose certain problems. In recent years, the combination of two or more standalone CO_2 capture technologies (hybrid processes) has attracted attention due to the potentially high capture efficiency and low energy requirement. This is done by combining two or more conventional technologies to negate their individual disadvantages, and to be superior overall (Freeman et al., 2014). These processes aim to take advantage of the strengths of each technique to improve the overall performance of the carbon capture system, such as improving the selectivity of the separation or reducing the energy requirements. Figure 2 illustrates the polymer-based adsorption process for CO_2 capture.

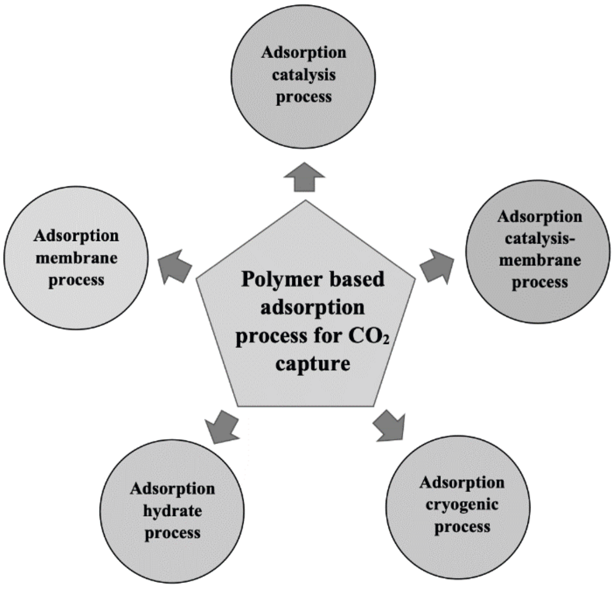

Figure 2: Polymer-based adsorption process for CO_2 capture.

4.1 Adsorption-catalysis processes

Adsorption-catalysis processes can be an approach for carbon capture and conversion. These processes involve the simultaneous use of an adsorbent and a catalyst to capture CO_2 and convert it into value-added products (Dai et al., 2017). The use of a catalyst enhances the selectivity and activity of the conversion process, while the use of an adsorbent can improve the overall efficiency of the system.

One example of an adsorption-catalysis process is the use of metal-organic frameworks (MOFs) as both adsorbents and catalysts. MOFs are porous materials that can selectively adsorb CO_2 from a gas mixture, while also providing an active catalytic site for the conversion of the captured CO_2. A study by Huo et al., 2023 demonstrated the use of a Zr-based MOF as an adsorbent-catalyst for the conversion of CO_2 into methanol, with a high conversion efficiency of 72.2%. Similarly, a study by Hsieh and others (Hsieh et al., 2022) used a co-based MOF as an adsorbent-catalyst for the conversion of CO_2 into formic acid, with a high selectivity of 94.4%.

Another example is the use of zeolites as adsorbents and catalysts for CO_2 conversion. Zeolites are crystalline materials that can selectively adsorb CO_2 while also providing a catalytic site for the conversion of the captured CO_2. A study by Mureddu et al., 2021 used a co-modified zeolite as an adsorbent-catalyst for the conversion of CO_2 into dimethyl ether, with a high conversion efficiency of 91.8%.

Adsorption-catalysis processes can be more sustainable than traditional carbon capture and conversion methods, as they can reduce the energy and material requirements of the overall system (L. Yang et al., 2022). Additionally, the production of valuable chemical products from CO_2 can create new economic opportunities and contribute to a more circular economy. However, further research is needed to optimize the performance of adsorption-catalysis processes and to scale up these processes for commercial use.

4.2 Adsorption-catalysis-membrane processes

Adsorption-catalysis-membrane (ACM) processes are a promising technology for CO_2 capture due to their high efficiency and low energy requirements. In these processes, the adsorption of CO_2 by an adsorbent material is combined with catalytic reactions and membrane separation to produce a purified stream of CO_2 (Chakrabortty et al., 2020). This approach offers several advantages over traditional absorption-based methods, including the ability to capture CO_2 from low-concentration sources and the potential to generate value-added products.

One example of an ACM process is the adsorption-catalysis-membrane hybrid system using a MOF adsorbent to achieve CO_2 capture capacity. The system also showed high stability and could be easily regenerated for repeated use (Elhenawy et al., 2020). A recent review by X. Gao et al., 2022 demonstrated the potential of an ACM system using a zeolite-supported amine adsorbent, a Cu-Mn oxide catalyst, and a polymeric membrane for CO_2 capture and conversion. The study showed that the membrane could effectively separate the reaction products from the reactants, which is critical for achieving high conversion rates and selectivity.

Overall, ACM processes offer a promising avenue for sustainable CO_2 capture and utilization. By combining the benefits of adsorption, catalysis, and membrane separation, these processes can improve the efficiency and sustainability of CO_2 capture and utilization technologies.

4.3 Adsorption-cryogenic processes

Adsorption-cryogenic (AC) processes are a type of CO_2 capture technology that uses low temperatures to separate CO_2 from a gas stream. In this process, CO_2 is adsorbed onto a solid adsorbent material at high pressure and low temperature and then desorbed by reducing the pressure and increasing the temperature (Gibson et al., 2016). The desorbed CO_2 is then liquefied by cooling to cryogenic temperatures, typically below -70°C, and separated from other gases using distillation or other separation techniques. This approach offers several advantages over other CO_2 capture technologies, including low energy requirements, high selectivity, and the ability to capture CO_2 from low-concentration sources.

One example of an AC process is the adsorption-cryogenic separation process using a zeolite 13X adsorbent, which was demonstrated by Nikolaidis et al., 2018 to achieve a CO_2 purity of over 95% and a recovery rate of up to 90% at a temperature of -78°C. The system also showed good stability over multiple cycles of operation.

Overall, AC processes offer a promising avenue for sustainable CO_2 capture and utilization. By using low temperatures and solid adsorbents, these processes can reduce energy requirements and improve the efficiency of CO_2 capture technologies (Ketabchi et al., 2023). Further research is needed to optimize the performance of AC processes and to develop new adsorbent materials with higher CO_2 uptake capacity and selectivity.

4.4 Adsorption-membrane processes

Adsorption-membrane (AM) processes are a promising class of CO_2 capture technologies that combine the advantages of adsorption and membrane separation. In this process, a gas mixture containing CO_2 is passed through a porous adsorbent material, where the CO_2 is selectively adsorbed onto the surface of the material (Webley, 2014). The adsorbed CO_2 is then transported through a membrane that selectively allows the passage of CO_2, while other gases are rejected. The separated CO_2 can then be collected, stored, or utilized.

One example of an AM process is the vacuum-pressure swing adsorption-membrane (VPSAM) process, which was demonstrated by Zarghampoor et al., 2022 to achieve a CO_2 capture efficiency of over 90% and a CO_2 purity of over 95% using a zeolite 13X adsorbent and a polydimethylsiloxane (PDMS) membrane. The system also showed good stability over multiple cycles of operation.

Recent advancements in AM processes have focused on developing new adsorbent materials and membrane technologies to improve the performance and efficiency of the process. For example, a study by Elsaidi et al., 2020 investigated the use of a composite adsorbent. The system demonstrated a CO_2 capture efficiency of up to 88% and a CO_2 purity of up to 99.6% at a pressure of 5 bar and a temperature of 25°C.

In conclusion, AM processes offer a promising approach for sustainable CO_2 capture and utilization, combining the advantages of both adsorption and membrane separation. Further research is needed to optimize the performance of AM processes and to develop new adsorbent materials and membrane technologies with higher CO_2 uptake capacity, selectivity, and permeance.

4.5 Adsorption-hydrate processes

Adsorption-hydrate processes involve the formation of clathrate hydrates, which are compounds formed when water molecules create a cage-like structure around a guest molecule (Kang et al., 2012), (Babu et al., 2014). These processes have been investigated for their potential to separate CO_2 from flue gas. The use of clathrate hydrates for carbon capture is still in the early stages of research, and there are several challenges to be addressed, such as the formation of hydrates under conditions that are not energy-efficient, the need for high-pressure systems, and the difficulty in separating the captured CO_2 from the hydrate (Kim et al., 2023). However, recent studies have shown promise for using clathrate hydrates as a potential carbon capture method. Combining hydrate formation with selective sorbents is one method for improving the kinetics of gas capture.

For instance, M. Yang et al., 2017 investigated the use of a mixed gas hydrate-based system for CO2 capture from flue gas and reported a high CO_2 capture capacity. Additionally, Hu et al., 2019 reviewed the potential of a novel composite adsorbent made of MOF and clathrate hydrates for the capture of CO_2 and found that the adsorbent had high selectivity for CO_2 over other gases. While these studies show promise for the use of adsorption-hydrate processes for carbon capture, more research is needed to overcome the challenges and fully understand the potential of this technology.

5. Overview of technical advancements in polymer-based adsorbents for CO_2 capture

Over the past decade, significant advancements have been made in the development of polymer-based adsorbents for CO_2 capture. These advancements include the synthesis of novel polymers, optimization of the pore structure, and modification of the surface chemistry to enhance the CO_2 adsorption capacity and selectivity (H. Chen et al., 2021). In particular, research has focused on the development of hybrid materials that combine the benefits of different polymer types, such as the combination of PEI with PVDF (M. Gao et al., 2022). Researchers have also investigated the use of functionalized polymers, such as amine-functionalized polymers, for CO_2 capture. The development of efficient regeneration techniques, such as thermal, pressure, and vacuum swing adsorption, has also been a focus of research. Furthermore, research has explored the use of polymer-based adsorbents in combination with other CO_2 capture technologies, such as membrane separation and cryogenic separation, to enhance overall performance as discussed. Overall, these technical advancements in polymer-based adsorbents have greatly improved their potential for use in large-scale CO_2 capture applications.

Despite the technical advancements in polymer-based adsorbents for CO_2 capture, there are still some limitations and challenges that need to be addressed. One major challenge is their low selectivity towards CO_2 in the presence of other gases, which can result in reduced efficiency and increased operating costs. Additionally, the regeneration of polymer-based adsorbents requires high energy consumption, which can offset some of their environmental benefits. Other challenges include their low durability, low mechanical strength, and susceptibility to chemical and thermal degradation over time. Addressing these limitations and challenges will be crucial for the widespread adoption of polymer-based adsorbents for CO_2 capture.

Other limitations of polymer-based adsorbents for CO_2 capture include their relatively low CO_2 uptake capacity compared to some other materials, such as zeolites and MOFs. In addition, some polymer-based adsorbents may be less selective for CO_2, which can result in lower purity of the captured gas. Another challenge is the stability of the adsorbent material, which can be affected by exposure to high temperatures, humidity, or chemical impurities in the flue gas stream. Finally, the cost and scalability of polymer-based adsorbents for large-scale CO_2 capture applications are also important considerations that need to be addressed for their commercial viability.

6. Sustainable developments in polymer-based adsorbents

6.1 Life cycle assessment of polymer materials and technology for carbon capture using adsorption

Life cycle assessment (LCA) is a comprehensive methodology used to assess the environmental impacts of a product, process, or service over its entire life cycle, from raw material extraction to final disposal. In the context of polymer materials and technology for carbon capture using adsorption, LCA can provide a holistic approach to evaluating the environmental sustainability of these materials (Rosenthal et al., 2020).

The use of polymer-based adsorbents for carbon capture involves several stages, including the production and disposal of these materials. During the production stage, energy consumption, raw material extraction, and transportation can contribute to the environmental impacts of polymer-based adsorbents (Sattari et al., 2021b). The disposal stage also needs to be considered, as these materials need to be safely disposed of after their service life.

Several studies have used LCA to evaluate the environmental impact of polymer-based adsorbents for carbon capture. For example, a study J. Chen et al., 2019 used LCA to assess the environmental impact of three types of polymer-based adsorbents for CO_2 capture. The study found that the production of these materials had the highest environmental impact, followed by the disposal stage. The results also showed that the use of renewable resources and energy-efficient manufacturing processes could significantly reduce the environmental impact of these materials.

LCA has been used to assess the environmental impact of various carbon capture technologies, including the use of adsorbents such as MOFs with MEA-loaded fibres. For example, Ling et al., (Tang et al., 2021) evaluated the life cycle environmental impact of carbon capture using MOFs with MEA-loaded fibres as the adsorbent and found that the process had a lower environmental impact compared to other technologies, such as amine-based absorption. While this study did not specifically evaluate polymer-based adsorbents, it highlights the potential of using adsorbents with a lower environmental impact for carbon capture. Future research should continue to explore the environmental impact of various types of adsorbents, including polymer-based adsorbents, using LCA, while also considering the specific operational and design factors that can affect their overall environmental impact.

Despite the potential of LCA in assessing the environmental sustainability of polymer materials and technology for carbon capture using adsorption, some challenges need to be addressed. For example, the lack of data on the environmental impact of some raw materials used in the production of these materials can affect the accuracy of LCA results. Moreover, the varying conditions of the production and disposal stages can also impact the environmental impact of polymer-based adsorbents.

6.2 Comparison of the environmental impact of polymer-based adsorbents with other adsorbents

While polymer-based adsorbents have been shown to have many advantages for CO_2 capture, it is important to compare their environmental impact with other adsorbent materials. A study by

R. Gonzalez-Olmos et al., 2022 compared the environmental impact of several types of adsorbents, including polymer-based adsorbents, activated carbon, and zeolites. The study found that while all these adsorbents had a lower environmental impact than traditional solvent-based CO_2 capture processes, polymer-based adsorbents had the lowest overall impact. Polymer-based adsorbents had lower impacts in categories such as global warming potential, ozone depletion potential, and acidification potential. However, the study did note that more research is needed to fully understand the life cycle impacts of different adsorbent materials and to ensure that any new materials developed are both effective and sustainable.

Another study by Sriram et al., 2022 compared the environmental impact of using different types of adsorbents, including polymer-based adsorbents, mesoporous silica, and MOFs. The study found that the use of polymer-based adsorbents had a lower environmental impact than other materials because they require less energy to regenerate and can capture CO_2 at low concentrations.

These studies highlight the importance of considering the environmental impact of different adsorbent materials when evaluating their potential for CO_2 capture and they suggest that polymer-based adsorbents can be a sustainable option compared to other materials.

6.3 Sustainable manufacturing of polymer-based adsorbents

These include using renewable feedstocks, such as biomass and waste materials, to produce the polymers, reducing the use of toxic solvents and chemicals, and using energy-efficient processes to minimize carbon emissions (Atiwesh et al., 2021). One example of a sustainable approach is the use of ionic liquids as solvents for polymer synthesis, which can reduce the need for toxic solvents and produce polymers with desirable properties. Additionally, using biodegradable polymers and incorporating recycled materials into the production process can further enhance the sustainability of polymer-based adsorbents. Overall, developing sustainable manufacturing strategies for polymer-based adsorbents is crucial for ensuring their long-term viability as a viable option for carbon capture and storage technologies.

There has been some research on the sustainable manufacturing of polymer-based adsorbents. A study by Kamarudin et al., 2022 explored the use of sustainable and eco-friendly approaches for the synthesis of polymer-based adsorbents for CO_2 capture. The study investigated the use of bio-based monomers and solvents, as well as the incorporation of natural fibres into the polymer matrix. The results showed that these sustainable approaches can significantly reduce the environmental impact of the adsorbent manufacturing process while maintaining high CO_2 capture performance. These studies suggest that sustainable manufacturing of polymer-based adsorbents is a promising area of research for reducing the environmental impact of CO_2 capture technologies.

Governments and societies around the world have implemented policies to support the sustainable manufacturing of polymer-based adsorbents for CO_2 capture. For example, the European Union's Horizon 2020 research and innovation program funds several research projects aimed at developing sustainable and cost-effective carbon capture technologies, including polymer-based adsorbents (R. C. Assunção et al., 2021). In the United States, the Department of Energy's Office of Fossil Energy funds research into advanced carbon capture technologies, including those using polymer-based adsorbents. Additionally, the Carbon Capture Coalition, a non-partisan group of businesses, labour organizations, and environmental organizations, advocates for policies that support the development and deployment of carbon capture technologies. These policies include tax credits and other financial incentives for companies that invest in carbon capture and storage technologies. Such governmental and societal support helps to incentivize and accelerate the development and deployment of sustainable manufacturing practices for polymer-based adsorbents.

In Asia, the Chinese government has implemented a series of regulations and policies to promote sustainable manufacturing practices (Tseng et al., 2013). The country has launched an action plan to promote green manufacturing, which aims to reduce the country's energy consumption and carbon emissions. The plan includes the establishment of green manufacturing demonstration zones, tax incentives for green manufacturing companies, and a green manufacturing certification system. Similarly, the Japanese government has set a target of reducing the country's greenhouse gas emissions by 80% by 2050. The government is promoting the use of renewable energy sources and has established a certification system for low-carbon products.

These are just a few examples of policies and regulations across the world that promote sustainable manufacturing practices.

7. Conclusion and future implications

In this work, the status and development of CO_2 capture processes through adsorption were reviewed, including hybrid processes. The polymers used in these processes along with their production were reviewed, and how that affects the overall technology. It is evident from the literature that polymer-based adsorbents have shown promise as effective and efficient materials for CO_2 capture and storage. Additionally, research efforts have focused on improving the performance of these materials, including enhancing their selectivity, capacity, and stability, and exploring their use in novel applications such as direct air capture.

However, there are still some challenges and research gaps that need to be addressed in this field. For example, further studies are needed to optimize the design and synthesis of polymer-based adsorbents to achieve higher adsorption capacity and selectivity, as well as better durability and stability under harsh operating conditions. Moreover, the scale-up of these materials to industrial levels is still a challenge that requires additional research and development. Furthermore, there is a need for more comprehensive life cycle assessments that consider the entire carbon capture and storage process, including the environmental impacts of polymer materials and their disposal after their service life. Finally, more research is needed to develop sustainable and cost-effective approaches for the regeneration of polymer-based adsorbents, as well as their integration with other carbon capture and storage technologies.

Among the studies reviewed in the past decade, it was noted that many studies do not emphasise the production of the adsorbent used, nor do they mention the solvents that might have been used for the polymer. A key area of concern should hence be the use of green solvents in the making of any adsorbents used, as well as in the carbon capture process. Further, hybrid processes have superior CO_2 recovery, less energy penalty and installation investment, and should be encouraged over standalone methods.

Although there is increasing research in carbon capture, current research is mainly confined to lab-scale or simulation studies. Additionally, despite major countries and organizations having developed carbon capture plants for over a decade, the amount of carbon actually captured and stored remains woefully inadequate, especially in comparison to the amount of carbon produced. The sector has missed every target that involved getting major industrial projects up and running, and it is on track to miss every future target. It is clear that a multidisciplinary approach is necessary to address the challenges associated with carbon capture and storage and to develop sustainable solutions that are both technically feasible and economically viable.

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