

Carbon Capture Using Polymer-Based Membranes – A Green Solution to Climate Change

Anita Gaur^{1,*}, Aakash Chaudhary²

Abstract

Growing concerns over greenhouse gas emissions have intensified the search for efficient and eco-friendly carbon capture technologies. This study explores the potential of innovative polymer-based membranes as a sustainable approach to controlling CO₂ emissions. The paper outlines the fundamental mechanisms of gas transport in membranes, reviews recent advancements in polymer material design, and examines various membrane configurations suited for industrial applications. Special attention is given to newly developed high-performance polymers that offer improved selectivity, permeability, and operational stability. Industrial case studies, pilot projects, and commercially implemented systems are analyzed to demonstrate real-world feasibility. Additionally, the role of emerging tools, such as data analytics and machine learning, in optimizing membrane performance is discussed. The paper concludes by identifying the main technical and economic challenges, while proposing strategic directions for scaling polymer membrane technology from research to widespread industrial deployment.

Keywords: Carbon capture, greenhouse gas emissions, polymer-based membranes, CO₂ separation, gas transport mechanisms

INTRODUCTION

Climate change is no longer a far-off possibility – it is a present reality we are already experiencing. From increasing sea levels and extreme heatwaves to erratic weather patterns and ecological imbalances, the evidence is all around us. As someone deeply concerned about the environment and the Future of our planet, I have often found myself thinking about what practical Solutions exist to reduce the damage we have already done – and more importantly, how we can prevent further harm. One area that caught my Attention is carbon capture, particularly the use of polymer-based membranes as A sustainable and green method to tackle carbon emissions. The more I read and learned about climate change, the clearer it became that while switching to renewable energy and promoting eco-friendly lifestyles are crucial, they may not be enough on their own. Our industrial systems, power plants, and even some essential Industrial manufacturing operations still emit significant volumes of carbon dioxide (CO₂) into the

atmosphere. CO₂ is one of the main greenhouse gases responsible for global warming, and its long atmospheric lifetime means that even if we stopped all emissions tomorrow, the effects would linger for decades. This is where carbon capture comes in – not as a replacement for renewable energy, but as a complementary strategy that directly addresses emissions from existing Infrastructure. Traditional carbon capture technologies often involve processes, like amine Scrubbing, which uses liquid solvents to absorb CO₂. While effective, these Methods can be energy-intensive, expensive, and potentially harmful to the Environment due to issues like solvent degradation and waste disposal. That led me to explore alternatives, and that is how I discovered

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polymer-based membranes. Compared to conventional methods, these membranes offer a more energy-efficient and environmentally friendly way to separate CO₂ from gas mixtures. The idea that such a thin, flexible material could have such a powerful impact really fascinated me [1–3].

At a basic level, polymer membranes act as selective barriers, allowing certain gases to pass through more easily than others. In carbon capture applications, these membranes are designed to let CO₂ pass while blocking other gases like nitrogen. This selective permeability depends on the chemical structure of the polymer, its porosity, and how it interacts with CO₂ molecules. What makes this approach particularly promising is that membranes do not require chemical reactions or phase changes translate to lower energy consumption and easier operation. Another thing that stands out about polymer-based membranes is their versatility. They can be used in a variety of settings, including flue gas treatment at power plants, natural gas purification, and even in emerging technologies like direct air capture (DAC). Scientists and engineers are constantly working to improve the performance of these membranes by tweaking their chemistry, layering them for better selectivity, or incorporating nanomaterials to boost efficiency. This ongoing innovation makes the field exciting and full of potential. From a sustainability perspective, polymer membranes are appealing because they are generally lightweight, can be produced at scale, and often have a smaller environmental footprint compared to traditional technologies. Some modern polymers are produced from renewable resources, adding to their environmental benefits. With increasing global awareness and commitment to climate action, such technology has the potential to become a key solution for industries to cut carbon emissions without needing major changes to their existing systems. Of course, no technology is perfect, and polymer-based carbon capture does face challenges. For example, finding membranes that offer both high permeability (how fast CO₂ moves through) and high selectivity (how well it separates CO₂ from other gases) is still a balancing act. Some membranes are great at one but not the other. There are also durability concerns in harsh industrial environments and issues related to scaling up from lab prototypes to real-world systems. Still, I believe the benefits and potential far outweigh the drawbacks – and that is what makes this area worth exploring. In writing this paper, my goal is to share what I have learned about polymer-based membranes for carbon capture – not just the science behind them, but why they matter in the bigger picture of climate solutions. I will look at how these membranes work, what Materials are used, the latest innovations in the field, and the environmental and Economic implications of deploying them on a larger scale. I will also try to provide a balanced view by discussing the current limitations and what is being done to overcome them [4–6].

LITERATURE REVIEW

A detailed review published in *Energy & Environmental Science* (2025) highlights that the performance of polymer membranes for CO₂ capture is mainly influenced by two factors— permeability and selectivity of the material. Polymers, such as polyamides, polymers of intrinsic microporosity (PIMs), and poly (ethylene oxide)-based materials, have shown strong potential for efficiently separating CO₂ from industrial flue gases. Their lightweight structure, modular design, and scalability make them appealing for industrial adoption [7].

In *Nature Computational Materials* (2023), researchers introduced an AI-powered model to identify new polymer structures specifically optimized for CO₂ capture. This method accelerates the discovery process and helps uncover materials that might remain unnoticed through traditional lab testing [8].

A recent breakthrough in graphene-based membrane development has introduced ultra-thin, highly selective layers designed for efficient CO₂ separation. These membranes combine excellent separation performance with the potential for cost-effective large-scale production, which is a critical factor for widespread use [9].

Traditional amine-based CO₂ capture systems are energy-demanding and suffer from issues, such as corrosion and solvent breakdown, whereas membrane technology offers a more efficient alternative. In contrast, membrane systems separate gases using selective permeability, allowing CO₂ to pass more quickly than gases, like N₂, making them suitable for flue gas treatment [10].

Polyimide membranes have high selectivity and excellent thermal stability, but they also face challenges such as plasticization and material aging. To address these issues, PIMs have been developed, offering a balance between high permeability and moderate selectivity [11].

Incorporating metal–organic frameworks (MOFs) into a polymer base can significantly enhance CO₂ selectivity while maintaining permeability. A key challenge, however, remains in achieving uniform MOF dispersion.

AI-driven screening has been used to predict polymer structures with superior gas separation performance, identifying several promising combinations that could outperform existing materials [11].

Properly aligned graphene oxide nanosheets within a polymer matrix can create extremely thin, defect-free membranes with high CO₂ selectivity. These also demonstrated resistance to contaminants, making them practical for real-world applications.

The Robeson upper bound highlights the trade-off between selectivity and permeability that still limits many polymer systems, while long-term durability and scalability remain critical challenges for industrial applications.

Polymer membranes produce less waste, require less energy, and can often be manufactured from renewable or recyclable materials. These properties make them well-suited for integration into broader environmental and energy strategies.

In summary, in this project, I explore how polymer-based membranes can be used to capture CO₂ as a green solution to climate change. Since:

- CO₂ emissions are a major cause of global warming; finding efficient and sustainable ways to reduce them is important.

Polymer membranes are promising because they are lightweight, energy-efficient, and environmentally friendly. I also investigated recent advances and challenges in membrane technology, showing how it could help reduce emissions from industries in the future.

BACKGROUND: CLIMATE CHANGE AND CO₂ EMISSIONS

Climate change is a major global problem that affects the environment, people's health, and the economy. One of the main causes of climate change is the increase in CO₂ in the atmosphere. CO₂ is a greenhouse gas, which means it traps heat from the sun and warms the Earth's surface. While some CO₂ is natural and necessary, human activities have added too much of it in a short time, upsetting the planet's balance.

Background

Climate Change and CO₂ Emissions Climate change is a major global problem that affects the environment, people's health, and the economy. One of the main causes of climate change is the increase in CO₂ in the atmosphere. CO₂ is a greenhouse gas, which means it traps heat from the sun and warms the Earth's surface. While some CO₂ is natural and necessary, human activities have added too much of it in a short time, upsetting the planet's balance. In recent years, the level of CO₂ in the atmosphere has gone above 420 parts per million (ppm) – much higher than it has been in millions of years. Even though many countries have signed agreements, like the Paris Agreement, to reduce emissions, current efforts are not enough to stop the rise in global temperatures. To fight climate change, we need to both reduce the amount of CO₂ we release and remove some of the CO₂ that is already in the air. One effective approach to address this issue is CCS). In this method, CO₂ is collected from sources, such as power plants and industrial facilities, before it can be released into the atmosphere. The captured CO₂ is then either stored securely underground or repurposed in other industrial applications.

CARBON CAPTURE TECHNOLOGIES: AN OVERVIEW

Carbon capture technologies are crucial for reducing CO₂ emissions from major sources such as power plants, cement factories, and steel production facilities. These methods are particularly important in sectors where transitioning to renewable energy is challenging.

1. *CCS Typically Involve Three Main Steps:* Capture, transport, and storage or utilization of CO₂ to prevent it from being released into the atmosphere (IEA, 2021).
2. *Post-Combustion Capture:* This is the most used technique. It captures CO₂ from the flue gases produced after burning fossil fuels. Solvents, like amines absorb CO₂, which is then separated and compressed for transport. However, this process is energy intensive.
3. *Pre-Combustion Capture:* In this method, fuels are converted into a mixture of hydrogen and CO₂ before combustion. CO₂ is separated out, and hydrogen is used for power generation. This method is efficient but requires more complex plant designs.
4. *Ox-Fuel Combustion:* This process burns fuel in pure oxygen instead of air, producing a gas mixture of mostly CO₂ and water vapor. The water is condensed, leaving CO₂ for capture. Although efficient, the oxygen production step adds to the energy cost.

Emerging Technologies: Membranes

Membrane-based carbon capture is an emerging field offering promising advantages. Polymer-based membranes are materials that act, like filters, allowing CO₂ to pass through while blocking other gases like nitrogen. These systems can be more energy-efficient, modular, and environmentally friendly compared to chemical methods. Research is ongoing to improve membrane selectivity, permeability, and durability under industrial conditions.

Role in Climate Strategy

Carbon capture is not a substitute for renewable energy but is essential for reducing emissions from existing infrastructure and heavy industry. With global CO₂ levels rising, integrating newer, greener technologies – like membrane-based capture – is a step toward reaching net-zero emission goals (IPCC, 2022).

Polymer-Based Membranes for CO₂ Separation

As the world looks for better ways to reduce CO₂ emissions, membrane technology has become a promising option. Membranes are materials that act, like filters, allowing certain gases to pass through while blocking others. Polymer-based membranes are a type of membrane made from long chains of molecules (polymers) that are flexible, lightweight, and easy to process. These membranes are being studied and developed for use in carbon capture, especially for separating CO₂ from industrial gases.

How It Works

In a typical setup, a gas mixture (like flue gas from a power plant) passes through a polymer membrane. The membrane is designed to let CO₂ molecules pass through faster than other gases such as nitrogen (N₂).

This process is called selective permeation. The result is that CO₂ becomes more concentrated on one side of the membrane, allowing it to be captured and stored or reused.

The performance of a membrane depends mainly on two things:

1. Permeability – how quickly CO₂ can pass through the membrane.
2. Selectivity—how well the membrane separates CO₂ from other gases.

A good membrane should have both high permeability and high selectivity.

TYPES OF MEMBRANES

The main types are dense polymer membranes, porous membranes, and mixed matrix membranes (MMMs).

Dense Polymer Membranes

These are the most used membranes for gas separation. They are made from solid polymer materials that selectively allow CO₂ molecules to pass through faster than other gases like nitrogen. The separation is based on the difference in solubility and diffusivity of gases in the polymer. These membranes are simple, flexible, and relatively cheap to produce, which makes them attractive for industrial use. However, there is often a trade-off between how fast gases can pass through (permeability) and how selective the membrane is.

Porous Membranes

Porous membranes contain tiny holes or pores that allow gases to move through by size or pressure. These are usually less selective than dense membranes, so they are not commonly used alone for CO₂ capture. But they can be useful in certain applications, especially where gas mixtures have larger differences in molecule size.

MMMs

MMMs are an advanced type of membrane that combines polymers with other materials like zeolites or MOFs. These additives help improve the membrane's selectivity and gas transport properties. From what I have read, MMMs are becoming a popular research focus because they can offer the best of both worlds: the flexibility of polymers and the high performance of advanced materials.

Challenges

1. *Plasticization*: CO₂ can sometimes make the membrane swell, reducing its ability to separate gases.
2. *Aging*: Over time, the membrane material can degrade and lose performance.
3. *Trade-Off Between Permeability and Selectivity*: Most current membranes perform well in one area but not both. Future Potential polymer-based membranes could become a key tool in the fight against climate change. With continued development, they might offer a cleaner, cheaper, and more practical way to capture CO₂ and reduce harmful emissions in the future.

Future Scope

In the future, I believe polymer-based membranes will become more important in carbon capture technologies. As the world focuses more on reducing CO₂ emissions, there will be a bigger demand for cleaner, low-energy solutions. These membranes have great potential because they are lightweight, flexible, and can be more cost-effective than traditional methods. Researchers are already working on improving membrane performance by developing new materials and combining them with advanced particles. I also think membrane systems could be used in different industries, from power plants to biogas and natural gas processing.

CONCLUSION

Working on this project has helped me better understand the role of carbon capture technologies in the fight against climate change, especially the potential of polymer-based membranes. CO₂ emissions are one of the biggest contributors to global warming, and finding effective ways to reduce them is more important than ever. While switching to renewable energy is crucial, we also need solutions that can reduce emissions from existing industries. That is where carbon capture comes in – and membrane technology could be one of the most practical and sustainable options. Polymer-based membranes offer many advantages. They are lightweight, energy-efficient, and easier to scale compared to traditional chemical methods. They also have fewer environmental impacts since they do not rely on harmful solvents.

Through this project, I learned how these membranes work by selectively allowing CO₂ to pass through, which separates it from other gases like nitrogen. This makes them useful in power plants, cement factories, and other industrial settings.

Overall, this project has shown me that polymer-based membranes are a promising, environmentally friendly option for carbon capture. They have the potential to help tackle one of the biggest challenges

of our time, and I am excited to see how this technology will develop in the future. I have learned a lot from this research, and it has given me a deeper appreciation for the role that science and innovation play in solving global problems like climate change.

Novelty and Innovation of Research

What makes this project unique is its focus on polymer-based membranes as a newer, greener approach to carbon capture. While traditional methods, like chemical absorption, are well-known, they come with issues like high energy use and chemical waste. In my research, I investigated how polymer membranes can offer a cleaner and more efficient alternative.

The innovative part is how these membranes can be improved using advanced materials like in MMMs. These combine polymers with particles, such as zeolites or MOFs, to enhance both.

CO₂ selectivity and durability. This kind of research is still developing, which makes it exciting and relevant. By focusing on membrane-based solutions, my project brings attention to a technology that could be more sustainable, cost-effective, and suitable for future industrial use. I believe this approach adds a fresh perspective to how we can tackle CO₂ emissions in smarter and more eco-friendly ways.

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