



# Bio-Inspired Membrane Designs for Sustainable Chemical Separation: A Comprehensive Review

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## INTRODUCTION

The quest for sustainable chemical separation technologies has intensified in response to global environmental challenges and the need for efficient resource utilization. Bio-inspired membrane designs, inspired by natural processes and structures, have emerged as a promising solution in the field of membrane science. These membranes leverage the principles of biomimicry to enhance separation performance, improve energy efficiency, and minimize environmental impact. This review examines the advancements in bio-inspired membrane designs for sustainable chemical separation, highlighting key innovations, mechanisms, and future directions.

## DESCRIPTION

### Understanding bio-inspired membranes

Bio-inspired membranes mimic the unique structures and functions of biological membranes found in nature. Biological membranes possess remarkable selectivity, permeability, and resilience, which are critical for processes such as nutrient uptake and waste removal in living organisms. Researchers have sought to replicate these characteristics in synthetic membranes by utilizing natural materials and bio-inspired architectures. These membranes often incorporate features such as nanopore structures, hierarchical organization, and selective surface chemistry, enhancing their ability to separate specific molecules efficiently.

### Key innovations in bio-inspired membrane designs

Recent advancements in bio-inspired membrane designs have focused on integrating natural materials, such as cellulose, chitin, and silk proteins, into membrane structures. These biopolymers offer several advantages, including biodegradability, low toxicity, and renewable sourcing. For instance, cellulose-based membranes have demonstrated excellent mechanical

properties and tunable permeability, making them suitable for various chemical separation applications.

In addition to natural materials, the incorporation of biomimetic structures has proven effective in enhancing membrane performance. Inspired by biological systems, researchers have developed membranes with nanoscale features that mimic the selective transport mechanisms observed in nature. For example, membranes with nanoscale channels resembling aquaporins water channels found in cell membranes have shown improved water permeability and selective ion transport, making them ideal for desalination and water purification.

### Mechanisms of bio-inspired separation

Bio-inspired membranes utilize various mechanisms for chemical separation, including size exclusion, affinity interactions, and diffusion. Size exclusion is a fundamental principle where the membrane selectively allows smaller molecules to pass while rejecting larger ones. This mechanism is enhanced in bio-inspired membranes through the design of nanoporous structures that mimic the natural filtration processes observed in biological membranes.

Affinity interactions play a significant role in the selective separation of specific molecules. Bio-inspired membranes can be engineered with functionalized surfaces that exhibit selective binding properties. For instance, membranes modified with specific chemical groups can selectively attract and retain target molecules, facilitating efficient separation processes. This approach is particularly valuable in applications such as wastewater treatment and resource recovery, where selective removal of contaminants is essential.

Diffusion is another critical mechanism in bio-inspired membrane separation. By leveraging biomimetic structures, researchers have developed membranes that promote selective diffusion pathways for specific molecules. These membranes can enhance the transport of desired molecules while hindering the

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passage of undesired species, resulting in improved separation efficiency.

### Applications in sustainable chemical separation

Bio-inspired membranes have found applications in various fields, including water treatment, gas separation, and biochemical processes. In water treatment, bio-inspired membranes have demonstrated excellent performance in removing pollutants and contaminants from wastewater. For example, membranes incorporating natural polymers and nanostructures have shown enhanced rejection of heavy metals, organic compounds, and pathogens, contributing to cleaner water sources.

In gas separation, bio-inspired membranes offer innovative solutions for carbon capture and hydrogen separation. By mimicking the selective gas transport mechanisms of biological systems, researchers have developed membranes capable of selectively capturing CO<sub>2</sub> from flue gases while allowing the passage of nitrogen and oxygen. This technology is vital for mitigating greenhouse gas emissions and supporting climate change initiatives.

Furthermore, bio-inspired membranes are being explored in biochemical processes, such as enzyme separation and protein purification. These membranes can selectively retain biomolecules while allowing the passage of smaller impurities, enhancing the efficiency of bioprocessing applications.

### Challenges and future directions

While bio-inspired membranes present significant advantages, challenges remain in their development and implementation.

One of the primary challenges is achieving consistent and scalable production methods for bio-inspired membranes. Ensuring reproducibility in membrane performance is crucial for commercial applications.

Another challenge lies in the stability and durability of bio-inspired membranes under harsh operating conditions. Research is ongoing to improve the chemical and thermal stability of these membranes while maintaining their selective properties.

Future directions in bio-inspired membrane research include the exploration of hybrid designs that combine natural materials with synthetic polymers to enhance performance. Additionally, advances in nanotechnology and surface modification techniques will enable the creation of membranes with tailored properties for specific applications.

## CONCLUSION

Bio-inspired membrane designs represent a significant advancement in sustainable chemical separation technologies. By mimicking the structures and functions of biological membranes, these membranes offer enhanced selectivity, permeability, and environmental sustainability. As research progresses, bio-inspired membranes are poised to play a pivotal role in addressing global challenges in water treatment, gas separation, and biochemical processes. Continued innovation and collaboration between materials science and biomimicry will drive the development of next-generation membranes, paving the way for more efficient and sustainable chemical separation solutions.