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Review

State-of-the-Art Advances and Current Applications of Gel-Based Membranes

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Abstract: Gel-based membranes, a fusion of polymer networks and liquid components, have emerged as versatile tools in a variety of technological domains thanks to their unique structural and functional attributes. Historically rooted in basic filtration tasks, recent advancements in synthetic strategies have increased the mechanical strength, selectivity, and longevity of these membranes. This review summarizes their evolution, emphasizing breakthroughs that have positioned them at the forefront of cutting-edge applications. They have the potential for desalination and pollutant removal in water treatment processes, delivering efficiency that often surpasses conventional counterparts. The biomedical field has embraced them for drug delivery and tissue engineering, capitalizing on their biocompatibility and tunable properties. Additionally, their pivotal role in energy storage as gel electrolytes in batteries and fuel cells underscores their adaptability. However, despite monumental progress in gel-based membrane research, challenges persist, particularly in scalability and long-term stability. This synthesis provides an overview of the state-of-the-art applications of gel-based membranes and discusses potential strategies to overcome current limitations, laying the foundation for future innovations in this dynamic field.

Keywords: gel; membrane; biomedical applications; water treatment; energy storage

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1. Introduction

The concept of membranes can be traced back to ancient civilizations, where simple forms of filtration using natural materials like sand, gravel, and charcoal were employed to purify water [1]. The 19th century saw the birth of dialysis; in 1861, Thomas Graham described the process of separating dissolved substances using "parchment or some analogous membrane" [2]. In the early 20th century, researchers began to use cellulose-based materials to make membranes. In the 1960s, the development of asymmetric cellulose acetate membranes led to the commercialization of the reverse osmosis process, a significant breakthrough for desalination and water purification. Around the same time, ultrafiltration membranes were developed using new polymer materials, enhancing their ability to separate macromolecules. In the latter half of the 20th century, there was significant interest in gas separation [3]. Membranes became a focus for separating gases such as oxygen and nitrogen from air. With the advancement of nanotechnology, new materials like zeolites, metal-organic frameworks (MOFs), and carbon-based materials (e.g., graphene oxide) started being explored for membrane fabrication. Membranes began to be designed not just for separation but also for additional functions such as catalysis, sensing, and

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Abbreviations

MOFs	metal-organic frameworks
PVA	polyvinyl alcohol
PAM	polyacrylamide
PEG	polyethylene glycol
LbL	Layer-by-Layer
CIP	cleaning-in-place
Ag	silver
Au	gold
TiO_2	titanium dioxide
ZnO	Zinc oxide
RO	Reverse Osmosis
FO	Forward Osmosis
ED	Electrodialysis
LIBs	Lithium-Ion Batteries
PEMFCs	Proton Exchange Membrane Fuel Cells
DMFCs	Direct Methanol Fuel Cells
VOCs	Volatile Organic Compounds
PCL/Gel	polycaprolactone/gelatin
EDC/NHS	1-Ethyl-3-(3-dimethylaminopropyl)-carbodiimide/N-hydroxysuccinimide
PVA	polyvinyl alcohol
CS	Chitosan
XG/GG/HA	xanthan gum/gellan gum/hyaluronan hydrogel
PAM	polyacrylamide
DN	Double network
DEA	N,N-diethylacrylamide
DMA	N,N-dimethylacrylamide
PVDF-HFP	poly(vinylidene fluoride-hexafluoro propylene
PBMA	poly (butyl methacrylate)

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