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Towards sustainable ultrafast molecular-separation membranes: From conventional polymers to emerging materials

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ABSTRACT

Ultrafast molecular separation (UMS) membranes are highly selective towards active organic molecules such as antibiotics, amino acids and proteins that are 0.5–5 nm wide while lacking a phase transition and requiring a low energy input to achieve high speed separation. These advantages are the keys for deploying UMS membranes in a plethora of industries, including petrochemical, food, pharmaceutical, and water treatment industries, especially for dilute system separations. Most recently, advanced nanotechnology and cutting-edge nanomaterials have been combined with membrane separation technologies to generate tremendous potential for accelerating the development of UMS membranes. It is therefore critical to update the broader scientific community on the important advances in this exciting, interdisciplinary field. This review emphasizes the unique separation capabilities of UMS membranes, theories underpinning UMS membranes, traditional polymeric materials and nanomaterials emerging on the horizon for advanced UMS membrane fabrication and technical applications to address the existing knowledge gap. This work includes detailed discussions regarding existing challenges, as well as perspectives on this promising field.

Abbreviations: 2D, 2-dimensional; 3D, 3-dimensional; BCPs, block copolymers; CVD, chemical vapor deposition; COFs, covalent organic framework; DLC, diamond like carbon; EDTA, ethylene diamine tetra acetic acid; EB, Evan's blue; FET, field-effect transistor; GO, graphene oxide; LDHs, layered double hydroxides; MB, methyl blue; MD, molecular dynamics; MOFs, metal organic frameworks; MWCO, molecular weight cut-off; NF, nanofiltration; PBI, polybenzimidazoles; PDMS, polydimethylsiloxane; PSS, poly(sodium 4-styrenesulfonate; PS-b-PMMA, polystyrene-b-poly (methyl methacrylate; PS-b-P4VP, poly (styrene-b-4-vinylpyridine); PEI, polyethylenimine; PAFs, porous aromatic frameworks; PMP, poly(4-methyl-2-pentyne); PI, polyimides; PTMSP, poly[1-(trimethylsilyl)-1-propyne]; PIM, polymer intrinsic microporosity; Rh B, Rhodamine B; SWCNTs, single wall carbon nanotubes; SRNF, solvent-resistant nanofiltration; SPEK, sulfonated polyetherketone; TMOs, transition metal oxides; TMDs, transition metal dichalcogenides; WS_2, tungsten disulfide; UF, ultrafiltration; UMS, ultrafast molecular-separation.

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1. Introduction

Separation processes are fundamental in the biopharmaceutical, food, agricultural, chemical and petrochemical industries. Traditional separation techniques commonly used in these industries include distillation, pressure- and temperature-swing adsorption, and extraction. These technologies have high carbon footprints and are energy intensive. Compared with traditional separation technologies, membrane separation is more attractive due to its low carbon footprint, small spatial requirements and a lack of a phase transition in most cases [1–17]. In recent years, the impending global energy shortage and various environmental issues have accelerated the development of membrane separation, particularly in membrane assembly using nanotechnology and scale-up translations of membrane science for commercialization [1–17]. Membrane science typically involves chemical synthesis, material science, advanced characterization techniques, membrane manufacturing and modification, module design and process engineering. Therefore, advances in membrane science can simultaneously evolve separation techniques in practical industries and facilitate progression in related science and manufacturing industries.

Membrane separation is typically deployed to extract products (active molecules) from solvents or purify solvents for recycled use. The size of most aqueous organic contaminants and active molecules such as antibiotics, amino acid, dyes and some proteins is between 0.5 and 5 nm. Ideal separation techniques that isolate these molecules are the pore-size-dominated separation processes of nanofiltration (NF) and ultrafiltration (UF) [7–11]. In these processes, solutes are separated from aqueous solutions and organic media. Conventional molecular-sieving NF/UF membranes are fabricated using thick layers of selective polymeric materials with low porosities and broad pore size distributions, limiting their applications [18–22]. Based on the Hagen-Poiseuille equation, the solution flux is proportional to the pressure difference across the membrane and the porosity, and it is inversely proportional to the membrane thickness [23]. Therefore, the thickness and porosity of the selective layer are critical for obtaining polymeric membranes with high flux. Ultrathin membranes with additional passageways for molecular transportation can be fabricated by a combination of advanced nanotechnology, contemporary membrane materials, membrane fabrication strategies, and emerging engineering processes. The 0.5–5 nm pore size of these membranes is ideal for separating/removing organic molecules from water or solvents. As these membranes are usually deployed for separating dilute solutions, the solvent permeances (solvent flux) of such membranes are several orders of magnitudes higher than commercial membranes [24–73] with comparable rejection under standard operating conditions and have attracted significant attention. Considering the features of this class of membranes, we named these membranes as ultrafast molecular separation (UMS) membranes for consistency in the current work. With improvements in separation efficiency, UMS membranes can replace traditional energy-intensive separation processes, especially for very dilute system separations with negligible concentration polarization. Potentially, UMS membranes can also become the mainstay separation technique for technologically important fields such as wastewater treatment, fine chemical separation, food processing, and pharmaceutical production. Hence, it is critical to update the scientific community on such advances. This review starts with the most important aspects of UMS membranes with unique pore sizes ranging from 0.5 to 5 nm, including their properties and unique advantages, followed by a detailed discussion on the theory underpinning ultrafast molecular transport. Through comparisons with traditional fabrication techniques, crucial fabrication approaches for UMS membranes is discussed in the next section. A further