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Taking selectivity to a new high

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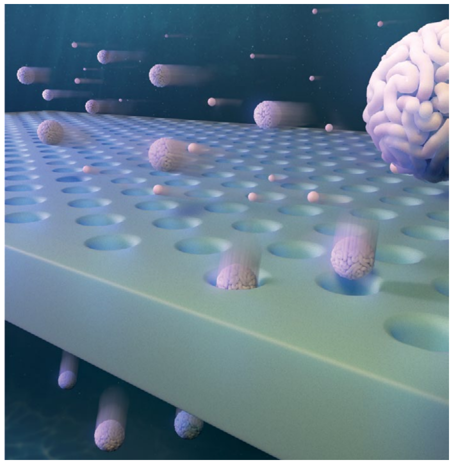
The ideal sharp cutoff of solutes by a porous membrane is not achievable yet. Prolonging the interactions between solutes and pores in isoporous membranes pushes the precise separation abilities further.

To address the challenge of water scarcity and supplement water supply, various technologies are developed to harness unconventional water sources such as seawater, brackish groundwater, and wastewater[1]. In the realm of desalination and water purification, membrane technologies are distinguished as one of the most prevalent methods, owing to their benefits in environmental impact, land utilization, user-friendliness, and versatility when contrasted with alternatives like thermal and chemical approaches[2].

Membranes are generally recognized to be limited by a selectivity–permeability trade-off[3]. Many commercial membranes feature numerous pores, enabling them to achieve high water permeability. However, despite their abundance of pores, their broad pore size distribution can restrict their size selectivity, thereby limiting their utility for both demanding and highly efficient separations[4]. Analyses indicate that enhancing water permeability beyond current levels would only marginally reduce energy demands and capital expenses[1]. Conversely, driven by diverse environmental requirements, enhancing selectivity should boost membrane efficiency, especially for water purification and resource recovery.

To achieve better selectivity, researchers have synthesized isoporous membranes featuring well-defined pores with large porosity and precise size. A viable design to achieve this involves utilizing block copolymers, which prompt the development of organized nanopatterns[5]. By using mixtures of different block copolymers, pore sizes can be tailored to achieve separation for different purposes.

In the separation process, it is intuitive to expect that solutes smaller than the membrane pores can pass through while larger ones are blocked. However, in practice, the separation of solutes of varying sizes is not always as precise, even in isoporous membranes with uniformly distributed pore sizes. In their Article, Feng Gao and colleagues fabricated ultrafiltration isoporous membranes using block copolymer self-assembly and a series of nanofabrication techniques and carefully operated filtration experiments and solute analyses to explore factors limiting the precise exclusion of solutes. They identify two critical factors affecting the sharp exclusion of solutes by membranes: preparation of isoporous membranes and sufficient interactions between solutes and the membrane. By effectively increasing the number of interactions within the defect-free isoporous membranes, a steeper size-selective rejection curve is achieved. The results break the limitation of the hindered transport theory, which emphasizes convective and diffusive hindrance in a pore.



Artistic rendition of solute rejection by an isoporous membrane.

The study and its implications are further discussed in the News & Views article by Anthony Straub. Specifically, Straub highlights the importance of entrance effects, which is neglected in the hindered transport theory, and is becoming even more important in ultrathin membranes such as single-atom-thick films, graphene films, and atomically smooth carbon nanotubes. Straub proposes several approaches in module configurations and process design to facilitate precise membrane separation, including hydrodynamic mixing to enhance solute–membrane interactions and nanotexturing to increase membrane roughness.

Despite the creation of consistently defect-free thin membranes for separation, scalability remains a challenge. Integrating block copolymers with nonsolvent-induced phase inversion provides a promising way to fabricate isoporous membranes for ultrafiltration on a large scale[6], but industrial-scale production of these membranes is rarely seen. One potential reason could be the marginal enhancement in water purification effectiveness achieved through the use of more costly block copolymers, as opposed to traditional polymers typically employed in membrane fabrication[7].

However, isoporous membranes are likely to have a more significant role in fields that involve the recovery of substances from various water bodies because of the need to realize ideal solute–solute separations[1]. For example, research on membranes has extensively explored lithium extraction from aqueous saline solutions. Yet, effectively isolating lithium from wastewater, which contains numerous coexisting ions of similar size to lithium, remains a significant challenge. Membranes featuring uniform pore sizes could offer a promising solution when integrated with carefully designed processes[8].

To effectively deploy isoporous membranes in practical settings, it is essential to conduct comprehensive, long-term system operations that account for process design requirements. Equally significant is understanding how the intricate compositions found in real water can influence membrane properties, potentially causing fouling due to diverse interactions between solutes and membranes. Thus, it is imperative to explore the application of uniform-pore-size membranes in real water scenarios, ensuring optimal utilization of the advancements offered by the next-generation membrane technology.

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References

1. Werber, J. R., Osuji, C. O. & Elimelech, M. *Nat. Rev. Mater.* **1**, 16018 (2016).
2. Yusuf, A. et al. *J. Clean. Prod.* **266**, 121867 (2020).
3. Waldman, R. Z., Gao, F., Phillip, W. A. & Darling, S. B. *J. Membr. Sci.* **633**, 119389 (2021).
4. Hampu, N., Werber, J. R., Chan, W. Y., Feinberg, E. C. & Hillmyer, M. A. *ACS Nano* **14**, 16446–16471 (2020).
5. Zhou, J., Huang, Y., Chen, C. & Wang, Y. *J. Membr. Sci.* **695**, 122467 (2024).
6. Peinemann, K.-V., Abetz, V. & Simon, P. *Nat. Mater.* **6**, 992–996 (2007).
7. Park, H. B., Kamcev, J., Robeson, L. M., Elimelech, M. & Freeman, B. D. *Science* **356**, eaab0530 (2017).
8. Zhao, Y. et al. *Environ. Sci. Technol.* **55**, 1359–1376 (2021).

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