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FIELD GRAND CHALLENGE
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Field Grand Challenge for Membrane Science and Technology

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INTRODUCTION

A membrane can be defined broadly as a physical barrier, which allows the selective passage of species from one side to the other under a driving force, or which controls the rate of permeation. Across the spectrum of separations or membrane processes, the species may be organic or aqueous liquids, solutes, vapors, gases, ions or electrons. An example of controlled transport of species is drug delivery. One of the advantages of a membrane process is the avoidance of a phase change, which may typically occur for conventional separation processes. Another advantage is the relatively small footprint of a membrane system, and its scalability and flexibility of onsite “at source” operation, for example, a small water treatment plant (Hoek and Tarabara, 2013; Baker, 2004).

The earliest accounts of membrane transport extend back over 200 years, and involved studies on biological as well as some synthetic membranes. Biological membranes are ubiquitous across the plant and animal kingdom, serving a multitude of functions. They have had eons to evolve intricate channels and pore structures and transport mechanisms with exquisite control over the permeation and selective passage of bioactive molecules, ions, water, and gases. In modern membrane science and technology, they serve as inspiration for the design of new membranes, through structural architecture or transport mechanisms. Much earlier work on synthetic membranes was on morphologies that could be thought of as having symmetric or dense structures, which had substantial resistance to transport, resulting in a low transmembrane flux of permeating species. While dense membranes enable the intrinsic properties to be studied in detail, draw useful structure-property relationships, and develop theoretic understanding of transport, they are impractical for industrial separation because of low product permeation.

The pivotal point in membrane science occurred in 1961, which was the start of the transformation from academic curiosity to industrial application. This was the development of the first practical membrane with sufficiently high water permeation for desalination of seawater, a process termed “reverse osmosis” (RO). It was an integrally-skinned asymmetric membrane with a thin selective layer made from cellulose acetate, developed by Loeb and Sourirajan, while at the University of California, Los Angeles (UCLA). Shortly after this, Sourirajan moved to the National Research Council (NRC), Canada, at the main Ottawa campus, and established a world-renowned membrane program that was to last several decades (Matsuura, 2020; Lau and Feng, 2021).

My long career and interest in membrane research began in January 1981 and spans about 4 decades. Having completed my Master’s degree in natural products chemistry at Carleton University, Canada in 1980, circumstances led me to return to Canada from the United Kingdom in January 1981, and I started a research contract on membrane materials at NRC. During my yearly NRC contracts, I completed my PhD at Carleton University while working at NRC, eventually becoming a Research Officer in 1987, at what was at that time, one of the major hubs of membrane research. Sourirajan's office was next to mine, separated by a glass door, and I often observed him and other prominent staff like Matsuura at coffee breaks with a large gathering of followers from many countries surrounding him (Matsuura, 2020) (note [1]).

Further landmarks in membrane science and technology came with the development of thin film composite (TFC) membranes, developed using interfacial polymerization by Cadotte in the 1970's. Thin selective layers were deposited upon mechanically robust inexpensive support membranes, allowing material decoupling of the support structure from the specialized selective layer, and this technology is the basis of most current commercial RO and nanofiltration (NF) membranes (Lu and Elimelech, 2021). The year 1980 heralded in commercial gas separation PRISM® membranes by Monsanto (now sold by Air Products), based on asymmetric hollow fiber polysulfone membranes. This was made possible by Henis and Tripodi's invention of a silicone caulking layer applied over the selective surface of the hollow fibers, to seal defects which would otherwise prevent good gas selectivity.

Since beginning my career in membrane science and technology, I have witnessed enormous changes in the field. What was a relatively small field and community back then has mushroomed into a burgeoning multidisciplinary area, with membrane centers situated in every corner of the globe. This is particularly evident in Asia, and especially in China, where I am currently situated, which in 20 years, has grown to be one of the largest contributors of journal articles in membranes, and with many innovative membrane companies and startups originating from large membrane centers. Helping the understanding and development of the field has been the widespread availability and adoption of advanced and sophisticated characterization techniques, as well as powerful computer modeling and molecular dynamics simulations.

Two main performance indicators for membranes are 1) the quantity of molecular components that permeate across the membrane under a driving force, and 2) how well the membrane can separate a mixture, or the purity of the component on the permeate side. The former parameter is often given as a permeability coefficient (i.e., a material property) or as flux or permeance (i.e., a membrane property). The later parameter is given as a separation factor, or an ideal or actual selectivity—the permeability of one component divided by another component. Many research articles emphasize the permeability–selectivity trade-off (Koros and Zhang, 2017; Park et al., 2017; Robeson, 2008; Swaidan et al., 2015). While these are key performance parameters, there is a multitude of other important membrane performance parameters, depending on the applications. These may include membrane materials practicality and uniformity, manufacture at scale, chemical, thermal, and mechanical stability, resistance to fouling, plasticization, and aging, and a host of other considerations. A majority of new membrane discoveries and those having ostensibly very good performance do not transition toward commercialization. This is because either a conventional separation process is tried and tested and works reliably, albeit at a substantially higher energy cost, or because of the large investment needed to take a material or membrane from academic work to industrial adoption poses too great a risk. One of the major challenges is in bridging the gap, and it requires a high level of engagement from both ends of the spectrum; academia and industry have entirely different needs and goals. Different timelines, project administration, exclusive licenses and the industrial need to protect knowhow and intellectual property conflict with academia's need to publish. National labs go some way to remedy this, but reporting requirements, bureaucracy, and the need for strict accounting of public funds may impede rapid progress. Smaller specialist startup companies appear to provide a way forward.

Perhaps clear messaging from industry, and more dialogue between industry and academia will help to better define the kinds of separation challenges that need to be solved, and just as importantly, those that are unlikely to adopt membranes because of status quo and too much required financial investment and unacceptable risk. The needs of industry are constantly evolving. The worldwide focus on the efficient use of energy, green energy production, environmental protection, recovery and reuse of water and valuable materials, and process intensification firmly place membrane science and technology in a strategic position to tackle some of the grand challenges the world faces, and displace some conventional energy-intensive separations (Drioli et al., 2011; Liu et al., 2018; Scholl and Lively, 2016). The scope of future membrane applications is expected to increase for a combination of reasons (Nunes et al., 2020). These may include societal needs for reducing energy use and increasing sustainability, as well as technical advances in making and manipulating novel materials for fabricating next-generation membranes (Qian et al., 2020; Wang et al., 2021; Wang et al., 2020; Zhang et al., 2018).

Membrane science and technology is multidisciplinary, and draws upon, polymeric and inorganic materials, chemistry, physics, chemical engineering, process engineering, mathematical modeling, among others. Necessarily, in attempting to divide up the journal into sections, there is overlap. Frontiers in Membrane Science and Technology seeks to become a premier journal covering a complete range of relevant topics, with an emphasis on novelty of approach, practicality, and high quality articles. A survey of current journal articles shows a tendency toward membrane materials, which is brought about by a more favorable academic reward structure in high impact journals (Beuscher et al., 2022). However, materials are really only just that, until they are transformed into membranes, which is the first of many steps toward membranes modules, membrane processes, and ultimately process integration. At journal launch, the following Sections are covered.

SPECIALTY SECTION: MEMBRANE FORMATION AND STRUCTURE

Specialty Chief Editor: Prof. Juhana Jaafar (Universiti Teknologi Malaysia)

The transformation of the vast array of different categories of materials into membrane structures with suitable morphology is the science of membrane formation and structure. To obtain

[1]Note During the preparation of the revision of this article, the death of Dr. Srinivasa Sourirajan on February 20, 2022 was announced in the Ottawa Citizen newspaper. https://ottawacitizen.remembering.ca/obituary/srinivasa-sourirajan-1084507224 [not available in Crossref].

membranes with practical properties such as high permeability or flux of a desired permeate, while having appropriate selectivity, often requires forming selective layers that are in the submicron range and less. A majority of membranes are made from polymers due to their processability, ease of membrane formation, and cost, while a smaller proportion are made from inorganic materials, either due to more defined pore structures, enabling high selectivity, or because of higher temperature processes or the need for high grade sterilization and foulant removal in food applications. Sol–gel chemistry is employed extensively to prepare ceramic membranes with selective layers (Cui, 2015), and the sol–gel membranes have been applied in a variety of applications, including liquid (Liu et al., 2021a) and gas separations (Kurt and Topuz, 2021; Anggarini et al., 2022). Polymeric membranes from commodity plastics are also used as supports for specialty materials coated as high selectivity ultrathin layers, made by interfacial polymerization as TFC membranes, or by other processes to deposit materials such as metal organic frameworks (MOF) or covalent organic frameworks (COF). Recently, micro-engineered membranes and printed membranes are being studied. Much research is done on mixed matrix membranes (MMM), whereby the processability of polymers is combined with the well-defined pore structures of more expensive fillers (Chuah et al., 2018). There is a temptation among researchers to combine newly discovered fillers into polymeric membrane materials, but it is important to truly understand the effect of the filler, whether it is to enhance flux or selectivity by filler pore structures, or whether it is from chain packing disruption, or from polymer–filler interfacial defects or surface chemistry. Apart from transport data, robust comparisons with state-of-the-art MMMs are needed along with the science, to avoid incremental research.

SPECIALTY SECTION: MEMBRANE TRANSPORT, MODELLING AND SIMULATION

Specialty Chief Editor: Prof. Xiao-Lin Wang (Tsinghua University, China)

To improve membrane performance, it is important to gain a fundamental understanding of the mechanism of transport at play in any given process, so that this understanding translates into knowledge of how to improve and design membranes. Transport mechanisms vary depending upon the type of process, the environment, charged or uncharged species, electrical potential, and many other factors. Selective layers are broadly categorized into dense or porous structures, with transport through dense layers often being described by the solution-diffusion model, as in the case of gas separation, and RO. However, there is a continuum of morphology across different types of membranes, which requires appropriate modeling (Tang et al., 2021). The advent of powerful computer modeling and simulation during recent years has greatly increased our understanding, description, and prediction of transport. Rather than treating computer modeling software as a "black box" it is important that the quality of the inputs into the model are rigorously defined and selected, so as to achieve quality data out.

SPECIALTY SECTION: MEMBRANE MODULES AND PROCESSES

Specialty Chief Editor: Prof. Nalan Kabay (Ege University, Turkey)

Membrane processes continue to evolve as energy efficient and effective separation processes and are still in rapid development for new applications in clean technologies. Separation of large volumes of diluted streams; recovery, reuse and recycling of substances such as water and raw materials, process intensification and optimization, energy reduction, etc. can be realized by using membrane-based processes (Koltuniewicz and Drioli, 2008).

The commercial markets on key technologies such as chemical design of high-performance materials for separation, morphological design of high-performance membranes, element and module design for high performance membranes, plant design and operation technology for various membrane processes are rapidly expanding. There will be a growing demand for the development of novel membrane systems and technologies in the 21st century, which will entail intensive research to attain much improved membrane performance and stability against fouling for water and wastewater treatment (Uemura and Henmi, 2008).

To develop an efficient membrane process needs a holistic approach. Apart from the development of new membrane materials, the incorporation of membranes into modules designed with suitable flow channels to reduce concentration polarization, pressure drop and fouling, etc. must be considered. Beyond that, it involves the incorporation of membrane modules into a membrane process at certain configurations and working conditions, and finally integration of the membrane process into the overall process for the industrial applications. For this, a multidisciplinary research approach will be needed, encompassing a spectrum from computational modeling, through materials design, and finally engineering (Beuscher et al., 2022). Thus, the emphasis of this section goes beyond membrane properties, and is focused on module designs optimized for cost, efficiency, reduced fouling and concentration polarization, pressure drop, spacers, hydrodynamic flow, etc. Various applications require membranes in different formats, such as hollow fibers, tubular, and flat sheet, which are packaged into modules such as spiral wound, hollow fiber modules, plate-and-frame flat sheet or submerged membranes for membrane bioreactor (MBR). The emphasis is also more on membrane integration into an industrial process, taking a more holistic viewpoint of the system as a whole. The main goal of this section is to reveal new possibilities and innovative pathways for engineering applications of membrane processes in various industrial and environmental problems.

SPECIALTY SECTION: MEMBRANE APPLICATIONS—LIQUID

Specialty Chief Editor: Prof. Yunxia Hu (Tiangong University, China)

Processing liquids is perhaps among the membrane applications most familiar to the general public. Membrane water desalination of seawater and brackish water using RO is widely adopted across water scarcity regions of the world. Very large commercial plants capable of producing millions of liters of water per day are relatively commonplace, with multibillion liters globally. RO is also widely employed to make ultrapure water used in the electronics industry. While these TFC RO membranes are considered as commodities and operate at high efficiency over the thermodynamic requirement to overcome the osmotic pressure, there is room for further improvements in chemical resistance to cleaning agents and performance (Lu and Elimelech, 2021). NF, UF, and MF are extensively used for wastewater treatment, water recycling, recovery of valuable components in water, and food processing, all of which require specific membrane characteristics and improvements in properties. Other types of membranes are used for MBR and forward osmosis (FO). One large area of membranes is medical, particularly haemodialysis. These hollow fiber membranes have become inexpensive commodities, and in many countries, are one-time use. Membrane separations in the liquid phase still have many opportunities to help address growing resource scarcity, recovery, and recycling. For example, rare earth metal processing and isolation using membranes may alleviate some of the environmental stress caused by conventional processes, while simultaneously increasing supplies of this commodity. Membrane separations or processes accomplished by the input of electrical energy are another category of liquid separations. These include electrodialysis (ED) which can desalinate water, treat wastewater, and recover or manufacture valuable compounds (Al-Amshawee et al., 2020; Gurreri et al., 2020; Huang et al., 2007; Uliana et al., 2021), and electrified membranes (EM) for water treatment applications (Sun et al., 2021).

Membranes in contact with water and aqueous feeds invariably undergo some degree of fouling, which is an important challenge to address in the utilization membranes in a number of areas, for example in RO, nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF). Foulants can originate from bacterial contamination or from compounds in the feed, for example tannins. Approaches to mitigate fouling often involve membrane surface modification chemistries as well as hydrodynamics. To enable more authentic fouling challenge experiments, longer-term tests of multiple hours or days, with fouling recovery cycles allow better evaluation of fouling response.

Several sophisticated designs of engineered pores allow ion sieving, and there are many opportunities for new discovery paths in this research areas. Examples of these include ion sieving using COFs (Sheng et al., 2021), MOFs (Jian et al., 2020) and nanocone pores that enable high ion permselectivity (Shehzad et al., 2019). Other approaches such as nanoscale control of internal inhomogeneity enhances water transport in desalination membranes (Culp et al., 2021).

While most membrane separations involving liquids are in aqueous media, an important and growing area is that of non-aqueous separations, particularly organic solvent nanofiltration (OSN). Designing membranes for this category has particular challenges, because formation processes for polymeric membranes typically involve casting solutions containing organic solvents (Galizia and Bye, 2018). However, some remarkable progress is being made in this exciting area (Jimenez-Solomon et al., 2016) (Karan et al., 2015) and there is the possibility of displacing conventional energy-intensive refinery processes (Lively, 2021).

SPECIALTY SECTION: MEMBRANE APPLICATIONS—GAS AND VAPOR

Specialty Chief Editor: Prof. Jong-Hak Kim (Yonsei University, Korea)

Gas separation is the separation of molecules of gases or vapors from one another, and should not be confused with particle filtration. One major advantage over conventional gas separation is the avoidance of a phase change, resulting in substantial energy reductions required for the process. Many polymeric gas separation membranes operate by the solution-diffusion mechanism, whereby gas molecules are sorbed on the upstream side, and diffuse to the downstream side by an applied pressure driving force. Gases have different sorption coefficients with various membrane materials and their kinetic diameters are also different, effecting separation. In mixed gas separations, there are often competing interactions, so multicomponent mixed gas separations provide a more meaningful profile of an actual feed gas separation (Sholl and Lively, 2022). Other types of membranes and associated mechanisms include facilitated transport, metal membranes selective only toward hydrogen, carbon molecular sieving, MOF, ceramic and zeolitic membranes, mixed matrix membranes, and intrinsically microporous and ultramicroporous membranes. Using membranes derived from the latter category as an example, there is currently intense research interest since the discovery of polymers of intrinsic microporosity (PIM) by Peter Budd and Neil McKeown (Budd et al., 2004). PIM membranes have helped to redefine the upper bounds (Swaidan et al., 2015; Wang et al., 2018; Comesaña-Gándara et al., 2019).

Commercial gas separation on a large scale began with Monsanto's PRISM® asymmetric membranes made from silicone-coated polysulfone hollow fibers in 1980. The main application was the recovery and reuse of valuable hydrogen from purge gas in ammonia production. Other commercial membranes and gas separation applications followed. Currently, major applications are hydrogen separations, nitrogen production from air, and the removal of carbon dioxide from natural gas, and more recently, biogas. The nitrogen produced is used for inert gas blanketing in industrial processes, and fuel tanks in aviation transport. Interestingly, cellulose acetate asymmetric membranes originating from those of Loeb-Sourirajan RO, are widely used over nominally superior polymers, because of their robustness in withstanding challenging and various feed gases and contaminants. Beyond some of the more minor commercial applications such as dehydration, there is currently much interest in carbon dioxide capture from high intensity emitters, due to the focus on greenhouse gases being implicated in climate change. Due to the vast volumes of flue gas to process, the focus is on membranes needing low pressure driving force and ultrahigh permeance, to keep capture costs competitively low. One area gas separation membranes have been identified in "Seven chemical separations to change the world" is olefin-paraffin separation, as a means to reduce the energy intensity of the current conventional processes (Scholl and Lively, 2016). Ethylene and propylene are needed in large volume and high purity for the plastics industry (Ren et al., 2020). These are among the most challenging separations to accomplish by membranes due to the chemical and size similarities of the feed gases, but some promising progress is being made (Qiao et al., 2020).

SPECIALTY SECTION: MEMBRANE APPLICATIONS—ENERGY

Specialty Chief Editor: Dr. Xianfeng Li (Dalian Institute of Chemical Physics, China)

One of the fastest growing areas of membrane submissions I have witnessed is membranes and separators for energy applications. This has occurred largely due to the world demand and movement toward clean power generation and energy storage for grid, transport, and electronic devices. In this section on Energy, the Journal will be competing with many other specialized journals in materials, batteries, power, electrochemistry, etc. Different from the other sections where molecular separation occurs, here membranes are central in energy transformation by either storage, generation, or energy input/output. Oftentimes, the membrane or separator is a barrier toward electrons, while allowing the selective permeation of charged species such as ions or molecules. Characteristically, the membranes carry positive or negative fixed charges, which allow the passage of ions (Shin et al., 2017; Shehzad et al., 2021). Fuel cell membranes, such as proton exchange membranes (PEM) and anion exchange membranes (AEM) face substantial hurdles in cost and durability, quite apart from their task of maintaining high ion conductivity under various adverse environmental conditions such as elevated temperature and reduced humidity (Mustain et al., 2020; Jiao et al., 2021), but some approaches to achieving longer-term stability have been achieved (Liu et al., 2021b; Liu et al., 2022). Submissions on these membranes should include cell data and cell durability over a reasonable time. Battery separators have other challenges, such as short circuit safety considerations. Flow batteries are of increasing interest for off-peak grid storage, due to their potentially lower costs and capacity to manufacture economically at scale (Zhang et al., 2019). Lithium ion (Goodenough and Park, 2013), lithium metal (Girishkumar et al., 2010), sulfur, and other batteries all have challenges to overcome to improve their lifetime, safety (Chen et al., 2021), and practicality. With decarbonizing transport, and sustainability as a focus, improving battery performance is central to achieving these goals. Evaluation of battery charge/discharge is essential to determine cycle and lifetime performance. Energy storage by supercapacitors is also a rapidly growing field (Poonam et al., 2019; Lim et al., 2019; Moon et al., 2022). Supercapacitors have advantages over conventional capacitors because they have a very long life cycle and rapid charge–discharge rates, high energy densities. Electrolysis is becoming a major topic of global interest for producing green hydrogen from intermittent green energy sources, such as wind power (Li et al., 2021). Reverse electrodialysis (RED) and pressure retarded osmosis (PRO) can also be considered under this section, since they involve energy output from salinity differences.

THE JOURNAL

Frontiers in Membrane Science and Technology is inclusive and welcomes high quality journal submissions from every corner of the community. The emphasis is on meaningful and innovative work clearly communicated and presented to the scientific community. Having previously served as an Editor for 12 years, I have evaluated thousands of submissions, and I would like to share a brief personal perspective on publication. With the deluge of scientific articles across every discipline, setting and maintaining high journal standards is essential to effectively capture the attention of busy researchers. An article of possible interest may lead a researcher to skim the title, abstract, figures, and conclusions. Titles should capture the main content or innovation you want to convey—keep it short, interesting, and don't try to include everything. Keywords should make it easy for your article to be found. Abstracts should distill the main points, and not include every minor detail. In my opinion, neat well-presented figures are crucial in capturing a reader's attention (Rolandi et al., 2011). Captions should be descriptive, guiding the reader to what they are actually looking at. All elements of a figure, such as insets, should be clearly legible, preferably with a less cluttered "sans serif" font (e.g., Arial) applied uniformly across all figures. Often, scale bars from the instrument have small font size and are not clearly discernable, so more visible scales should be inserted. The narrative of an article should flow logically in sequence, be interesting to read, and it should state the novel aspects, and how it compares with published work in similar area. The conclusions should be carefully prepared, and not added as an afterthought, as I have seen on many occasions. If the results fall short and are not as good as anticipated, be honest about it—reviewers may appreciate this. The important questions the authors should ask themselves is "is my work clearly presented, and does my work offer substantial new insights in terms of new approaches, or improved performance, and does it add value to the body of scientific literature in a way that has the potential to advance the field?"

AUTHOR CONTRIBUTIONS

The Field Grand Challenge article was written by MG.

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