# Special Issue on “Novel Membrane Technologies for Traditional Industrial Processes”


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*Abstract:*

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*Editorial*

# Special Issue on "Novel Membrane Technologies for Traditional Industrial Processes"

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## 1. Background

Traditional industries span multiple sectors, such as coal, iron and steel, textile, machinery, chemical engineering, shipbuilding, and construction materials. They are indispensable to the social economy but consume significant quantities of raw materials and energy and release myriads of waste. With rising population and expansion of urbanization, there is a higher demand for the supply of goods and services, the problem may be intensified. Raising awareness about sustainable development has led to an increased pressure on technological upgrades to enhance the capacity of traditional industries in conducting "responsible consumption and production" [1].

Membrane technology, in general, refers to membrane separation that covers a spectrum of processes involving various organic and inorganic membranes as selective mediums. Investigation into combining membrane technology with traditional industrial processes is abundant and has identified its potential and versatility in tackling problems concerning mass and energy efficiency [2,3]. The key strength of membrane separation processes as a whole as compared with others is due to process continuity, environmental friendliness, and low footprint [4]. For several specific membrane technologies, for example, pervaporation (PV) and gas separation (GS), energy efficiency is an extra bonus [5]. Given the above points, a widespread implementation of membrane separation in the traditional industrial sector is expected to bring about more social and economic benefits. The truth, however, is that the overall level for industrial adoption is, thus far, limited.

It is argued by some that "innovation management" is not efficient. The consequence comprises the "awareness gap" and delayed transfer of advanced technology to low- and medium-tech industries [6]. A more important factor for scientists and engineers to consider is the technical problems arising in the process of the combination. On the one hand, traditional industrial processes commonly consume multifarious raw materials that makes the mass flows more or less complex and, hence, gives rise to the impossibility of solely relying on a single membrane unit or a simple process [7]. To realize workable solutions, upstream and/or downstream operations with sound design are needed, which requires multidisciplinary coordination and a long lead time. On the other hand, the drawbacks of membrane technology constitute a setback for its attractiveness. The separation properties of some commercial membranes are not sufficiently high. And decline in separation efficiency often occurs during service [8]. Several critical issues for practically operating a membrane system, for example, the capital and operational costs, are closely correlated with membrane separation performance. Another point to be noted is the diversity in separation mechanisms and operation modes among the varied membrane processes. Therefore, the determinant for process efficiency is not merely membrane property. As for forward osmosis (FO), for instance, an energy efficient manner to handle draw solution (DS) will greatly facilitate its spread [9].

Obviously, the scope of the problems require a multi-dimensional effort for further actualizing the boon of membrane technology. Novel scientific and engineering approaches need to be developed to identify effective solutions for the challenges. This encourages us to compile this special issue of *Novel Membrane Technologies for Traditional Industrial Processes*. It is now available online at: https://www.mdpi.com/journal/processes/special_issues/membrane_processes.

## 2. Content in This Special Issue

Nine articles are selected for this special issue. In the form of research or review, they present us with the latest progress addressing several aspects critical for developing efficient membrane systems. The papers are grouped into five categories:

(i) Gas separation; (ii) Biorefinery; (iii) Forward osmosis; (iv) Membrane bioreactor; (v) Membranes with aquaporins.

### *2.1. Gas Separation (GS)*

A critical step for the effective operation of Integrated Gasification Combined Cycle (IGCC) is air separation for gasification. Membrane separation is an energy-efficient way, but lacks membranes with high selectivity. In Yang et al.'s work [10], on-stream catalytic cracking deposition (CCD) was applied to modify MFI-type zeolite membranes. Selectivity of the modified membrane with an alumina-containing ZSM-5 surface (~1.95) was slightly lower than that (~2.25) of modified membrane without a ZSM-5 surface, but the former membrane exhibited a permeance 15 times higher. The channel narrowing during CCD was constrained within the thin layer near the outer surface, due to the "gate" effect in the presence of a ZSM-5 surface. This helped avoid back diffusion of less permeable $N_2$. Attention was also directed to intercrystalline spaces for further improving selectivity.

The spectrum of utilization of natural gas has broadened in past decade. Seeburg et al. carried out low-temperature hydrogen production from natural gas via steam reforming with 47 vol% successfully and $H_2$ was generated at 350 °C [11]. The novelty of the work for obtaining this result is associated with two points. The first was the production of a natural gas stream enriched with liquefied petroleum gas (LPG) alkanes. *n*-butane enrichment in a process using zeolite membranes of type MFI (Mobile Five) was 37.6 and 22.6 vol% in permeate. Another is a highly active Rh catalyst. It was formed in situ on $Al_2O_3$ during the reaction of C1–C5 alkanes with steam. The active component in the resultant $Rh1/Al_2O_3$ compound was Rh in nanoparticles (1–3 nm). The reforming was performed with real natural gas.

A problem raised before applying natural gas for any purpose is the presence of acid gas (e.g., $CO_2$, $H_2S$). They will reduce the caloric value of fuel and cause corrosion of pipelines. For polymeric membranes used in natural gas treatment to remove $CO_2$, a severe challenge is performance degradation due to $CO_2$-induced plasticization. Zhang et al. composed a review of the advanced methods for suppressing plasticization of polyimide membranes [12]. These include thermally-induced crosslinking, chemical crosslinking, physical crosslinking, ultraviolet-radiation crosslinking, and blending.

### *2.2. Biorefinery*

Utilization of microalgae solely for obtaining biofuels is not an economically viable process. To solve the problem, several other aspects should be considered, such as inclusive $CO_2$ capture, water quality improvement, procurement of commodities, and products with high-added value. The work by Lorente et al. showed us an innovative downstream route for bringing down production cost [13]. Acid-catalyzed steam explosion was employed to disrupt cells, generate hydrolysis of carbohydrates and partial hydrolysis of proteins. Dynamic filtration produced a permeate containing water and monosaccharides and a retentate containing the lipids and proteins. The steam explosion operation cost varied between 0.005 $/kg and 0.014 $/kg of the microalgae dry sample, depending on the cost of fuel. Membrane filtration cost was about 0.12 $/kg of microalgae (in dry state).

The challenge for the commercial application of lignin lies with its heterogeneity in structure and the low-purity of lignin delivered in traditional fractionation. Concerning the second challenge, several researches paid attention to the supported ionic liquid membrane (SILM). The selected paper in this special issue made a more comprehensive study to identify the suitable materials for effective lignin extraction and purification [14]. Among the combination from five different membrane supports and nine ionic liquids (ILs), the one with IL of [BMIM][DBP] embedded in polytetrafluoroethylene (PTFE) demonstrated selective transport for target solutes.

### 2.3. Forward Osmosis (FO)

FO is an emerging and versatile membrane separation that derives its driving force from a highly concentrated draw solution (DS). DS regeneration step will consume energy, which renders the necessity to find methods that could reduce energy consumption. Long et al. conducted a review analyzing the types of energy applied in DS regeneration [15]. Some DS (e.g., natural sugar, fertilizer) can be directly used without recovery, constituting the most effective way of saving energy. Chemical reactions involving precipitation and redissolving capitalize on chemical energy. The biggest family may be related to the utilization of thermal energy. Technologies making use of magnetic energy via magnetic particles and solar energy via light-sensitive hydrogels were also introduced. The most common one is electricity. This work gives a clear guideline for research into DS in the future.

Thin-film composite (TFC) membranes are widely used in FO. Membrane performance deterioration due to degradation and the polyamide (PA) skin layer breaking off often occurs. The former is due to disinfectants cleaning, and the latter results from the different materials for the selective layer and substrate. Wang et al. proposed a new strategy to overcome the problem [16]. Dopamine (DA) was the only amine in the aqueous phase to react with trimesoyl chloride (TMC) during interfacial polymerization (IP). In the reaction, PDA particles formed by self-assembly led to significant π–π and hydrogen-bonding interactions between the active and support layers. Additionally, the ester bonds had higher resistance to active chlorine than amide bonds of conventional PA layers.

### 2.4. Membrane Bioreactor (MBR)

This review by Argurio focuses on photocatalytic membrane reactors (PMR), a combination of photocatalytic and membrane processes [17]. PMR is a relatively new membrane technology, and the pioneering work was performed by Anderson and coworkers using $TiO_2$-based membranes. This review is comprehensive as it introduces system configurations based on catalyst confinement, the influence of operation parameters, and materials selection and membrane formation. Within these parts, the advantages and limits of PMR were analyzed. The final section is selected case studies.

### 2.5. Membranes with Aquaporins

Aquaporins which are highly permeable for water molecules and resistant to contaminants and small molecules are receiving great attention from membranologists, particularly for water treatment. An important challenge for their utilization in membrane separation is associated with maintaining their integrity and performance during developing membranes with embedded and aligned aquaporins, while keeping support porous enough. The steps key to the solution designed by Wagh et al. included [18]: (1) The connection of Cysteine modified aquaporins (Aqp-SH) to the polymeric support covalently, which results in an aligned pattern of the proteins; (2) which results in the remaining sites on the support reacting with polyvinyl alcohol with long alkyl chains (PVA-alkyl) to seal the gaps without aquaporin molecules. The membranes with aquaporins exhibited much higher and more stable rejection towards inorganic salts.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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