Chapter

Introductory Chapter: An Overview of Recent Advances in Membrane Technologies

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1. Introduction

Environmental changes, global warming, and inappropriate planning are two sides of the worldwide water shortage coin [1–3]. **Figure 1** shows the status of different countries based on water-stressed scenario [4]. Based on United Nations report, more than 2 billion people will experience water scarcity by 2050 [4]. All the previous projections show the vitality of drinking water production and desalination technologies. Currently, there exist two main commercial water-treatment process classes including thermal-based processes (including multistage flash distillation (MSF), vapor compression (VC), and multieffect distillation (MED)) and membrane filtration processes (including reverse osmosis (RO), nanofiltration (NF), and related energy recovery devices (ERD)). Thermal processes were more common previously. However, membrane technologies are outweighing the older processes. Main reasons for RO desalination process growth have mentioned to be rapid technical advances along with its simplicity and elegance [5–9].

Despite all advances in the field, fouling in its different types (colloidal matters, organic fouling of natural and synthetic chemicals, inorganic fouling (scaling), and biological fouling (biofouling)) is the remaining issue of industrial membrane processes [9, 10]. Various types of fouling will result in feed pressure increment and higher operational costs, more frequent requirement of chemical cleaning of the modules and shortened lifetime of the membranes. Fouling types happen simultaneously and could affect each other. This is while biofouling is identified as the critical issue as it is imposed to the membrane surface by living and dynamic microbiological cells and viruses. As the biological attachment, division of the cells and colonization on the surface occurs, the microbiological species and the exopolymeric substance produced by them, create resistance to antimicrobial treatments and the resulted biofouling starts to impose bio-corrosion and lowering the performance of the system [11]. Exposure of the membrane systems to feed's biological contamination highly depends on the environmental factors of the feed itself (nutrient content, available biological species, temperature, light, turbidity, and currents (tides and waves)) [12]. Items under feed water and microorganism classes are related to the microorganism proliferation and conditions supporting their existence. This is while main efforts over process enhancement and modification of membranes are attributed to the membrane-specific properties such as composition and surface structure-characteristics (classified under the title of membrane properties). Apparently, the issue of biofouling could own various levels of severity in different locations. Biofouling is mentioned to be responsible for 45% of the overall fouling that occurred in nanofiltration (NF) and RO plants [13–16].

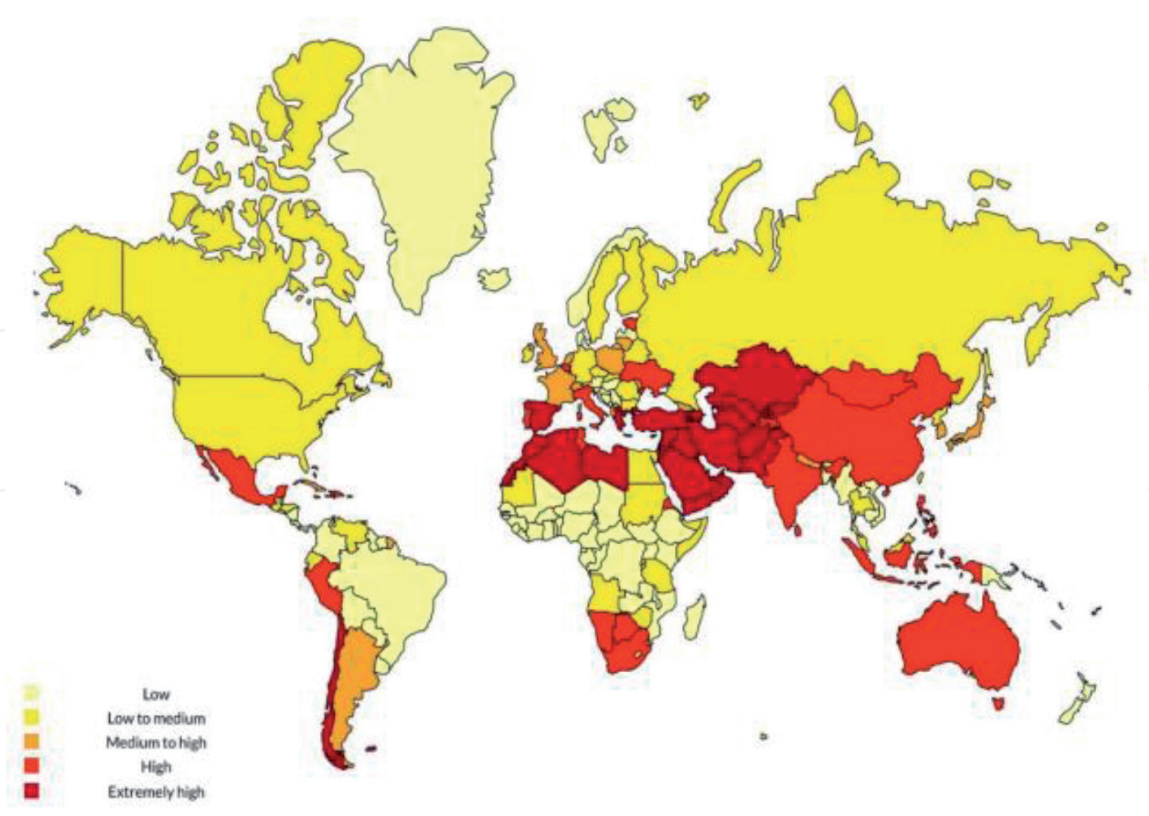

Figure 1.
Classification of water-stressed countries (based on water maps issued in [8]).

This is while FO processes as another prospective water treatment process, due to its inherent distinctions from pressure driven membranes processes, owns different fouling and biofouling profiles [17]. There have been several reviews covering different aspects of the process from material, technological, process, modeling, and economics aspects [18–30].

Another aspect of membrane-based water desalination technologies is their sustainability. Energy consumption optimization and recovery along with controlling footprint of the desalination plants have been focused more recently to further improve the technology [5]. Energy consumption in RO plants is mostly due to high-pressure pumps (more than 50% (**Figure 2**)) (energy consumption profiles in various plants might differ as water resource specifications are not identical). Groundwater resources are easier to treat and desalt in general as they are more restricted and less polluted [31]. Minimizing this energy input by using high-tech pumps, developing highly permeable membranes, eliminating fouling and biofouling issues on membrane surfaces and using energy recovery devices (ERD) [6, 32]. Another aspect, which has received more attention, is renewable energy-assisted water desalination renewable energy desalination (RED). Coupling desalination processes with clean renewable energy resources such as hydropower, wind, solar photovoltaic, geothermal, wave and tidal, etc. is an essential step in further improving the technology due to the high-energy demand of the processes [33, 34]. While RED plants are meant to be renewable energy dependent, they are commonly connected to the power distribution grid due to techno-economical limitations. Desalination plant capacity and renewable energy resource type could affect the final costs within these approaches. Several combination of renewable source and desalination technologies are considered individually and in a combined cycle. These combinations could be practical and promising depending on their scale, geographical characteristics of the installation, available technical infrastructures in the region, plant's remoteness, and access to electrical grid. Efforts for finding hybrid and newly developed low-cost processes have been addressed as a concern for sustainable water production [35].

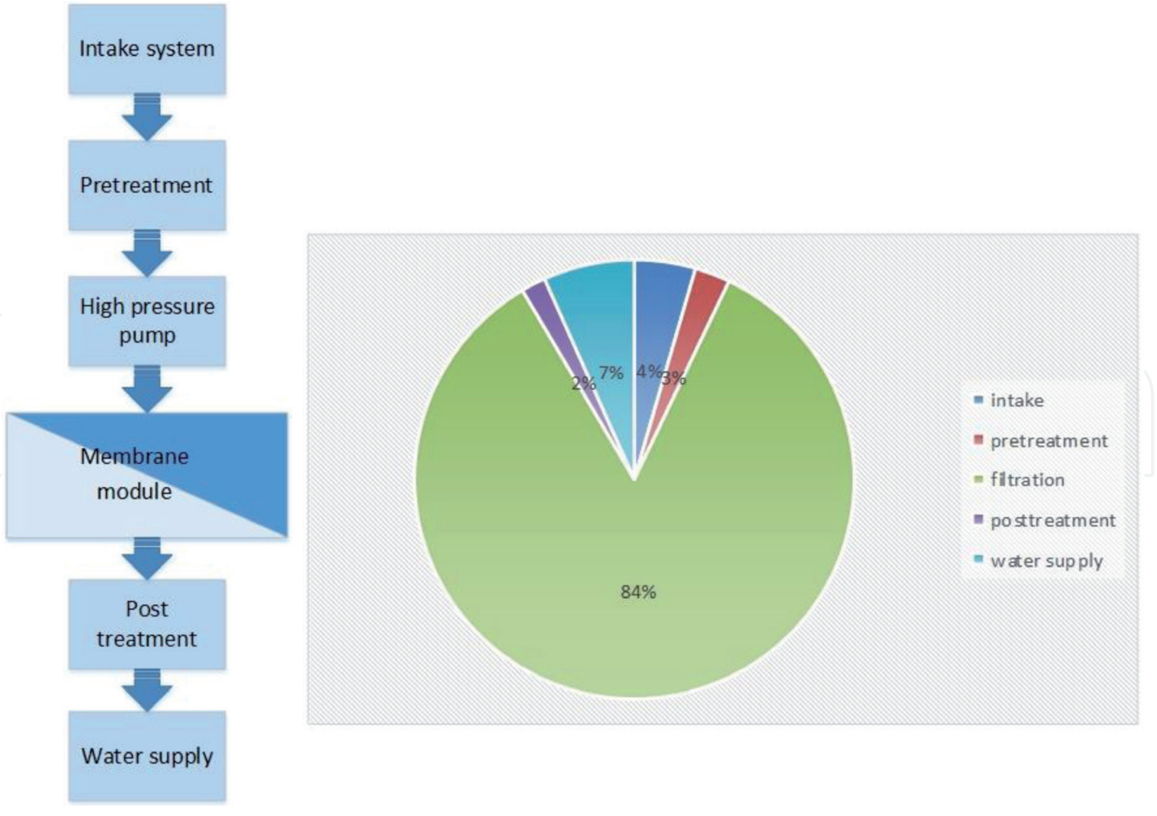

Figure 2.
Reverse osmosis process plant component and for energy consumption shares of total production cost.

While various advances in membrane technology are being reported, the only commercialized ones are polyamide (PA) thin-film composites and the rest are in fundamental development stage [36]. One of the emerging membrane technology candidates is forward osmosis (FO) also introduced as "direct osmosis," [37] "manipulated osmosis" [38], or "engineered osmosis" [39]. Despite the fact that it was introduced back in 1970s [40], the process has recently gained more attention. This is proved by grown number of publications since 2006–2016, with a total number of 1700 papers covering FO topics [17].

FO is based on a natural driving force, there is no need for external energy sources (rather than a small pressure) (around 2–3 bar to eliminate the frictional resistance on two sides of the membrane). This also means that less intense fouling occurs one the membrane surface in comparison with pressure-driven RO membranes [23]. Moreover, lower operating pressure means lower operating and capital cost due to less-pressure vessel incorporation in the plant [41]. Several proven applications of the process, such as concentration and dehydration, are efficiently put into practice. This is while the application of FO as a desalination process is not economical since it requires further purification step when it comes to water desalination [42].

In case of desalination, it is reported that the energy cost comprises 20–35% (with statistically higher reported values) of the final cost of the produced water, and this will change based on the size of the plant and the energy and electricity costs in each region [43]. Lower operation pressure and lower fouling profile in FO process have turned the process into an interesting membrane process, yet it cannot be considered as an alternative to RO in majority of applications. FO, in theoretical studies, is economical in comparison with pressure driven membrane processes if draw solution regeneration would not be needed. Yet, there is no practical justification to support theoretical studies at this time. Accordingly, process development researches must target such applications [44].

Rather than water treatment, academic researches over FO applications are reported in waste water treatment and recycling (municipal [45, 46], hospital [47, 48], landfill leachates [49, 50], pharmaceuticals [51, 52], industrial [53, 54]) salinity gradient based or pressure-retarded osmosis (PRO) power production [55, 56], trace organic treatment (pharmaceutical) [57–59], drink processing [60–62], and agriculture industries [63].

Rather than PRO process (which was failed practically in its only ongoing project), several other areas of energy production are taking advantages of membrane technologies, of which, most important ones are fuel cells [64] and biofuel production and purification [65]. Ion exchange membranes are subject of many intensive researches and the field has been improved intensively thanks to the engineering enhancement and material development for fuels cells [66–68]. Fuel processing and bio-based hydrocarbon production and purification areas are also taking advantages of membrane process. Rather than simple applications of oily waste waters resulted from the industry and filtration separation (complementary application of membranes [69, 70]), membrane-based process integration and intensifications have resulted in higher productivity. An instance of this would be transesterification membrane reactors for biodiesel production, which offers an ecofriendly, high quality product, low cost and small foot print fuel production path [71–73].

Integration and intensification or processes using membranes are a significantly highlighted section of the field. These include several concepts such as using simple and nonreactive membranes in a reactor as an extractor-contactor to remove one of the products in reaction environment so that the yield could be enhanced in an equilibrium reaction. Beside this, functionalized membranes (on the surface or within their structures) could act as catalysts and separated filters simultaneously [74]. Membrane-based process intensifications could result in lower consumption of energy, lower environmental footprint, lower required area, and higher efficiencies. This could finally result in a cheaper product such as processed fuels, purified, desalinated water, etc. [75–77]. **Table 1** offers different application of membranes in reactors as instances of process intensification opportunities for membranes.

Mutual application of membranes and nanoparticles is result in a new field of separation science entitled as mixed matric membranes (MMM) [78, 79]. More specifically, inorganic nanomaterials with specific properties such as antibacterially [11, 80], antifouling [81], photocatalytic behavior [82, 83], specific functional groups [84] for detailed purposes such as providing active binding sites for functionalization, etc. As nanomaterials could be synthesized with different and adjustable properties, MMMs could be tailor-made for specific target in gas-separation processes [85], thin-film-composite-assisted water desalination [86], forward-osmosis-assisted water desalination [87, 88], integrated waste water treatment and water desalination processes [89], fuel-cell-based energy production [90], valuable species recovery [91, 92], etc. Separation mechanisms could also be tunable as the MMMs would be governed by both solution-diffusion and sieving-sorption mechanisms [93]. More importantly, mechanical properties and stability of MMMs are generally improved as the structures are reinforced due to presence of inorganic phase [94]. **Table 1** offers a comparison between polymeric, inorganic, and mixed matrix membranes.

Membranes are also being intensively used in the area of biomedical applications and more specifically blood purification. Since its emerge back in 1960s, membranes were used as a main component of dialyzers in hemodialysis (HD) process [96]. Modules, membrane modalities, and membrane materials in HD have experienced a huge improvement so far [97–101]. All modifications have targeted more efficient clearance of uremic toxins and controlling body originated mediators

Membranes	Advantages	Disadvantages
Polymeric membranes*	Easy synthesis and fabrication Low production cost Good mechanical stability Easy for upscaling and making variations in module form Separation mechanism: Solution diffusion	Low chemical and thermal stability Plasticization Pore size not controllable Follows the trade-off between permeability and selectivity
Inorganic membranes*	Superior chemical, mechanical, and thermal stability Tunable pore size Moderate trade-off between permeability and selectivity Operate at harsh conditions Separation mechanism: molecular sieving (<6 Å), surface diffusion (<10–20 Å), capillary condensation (<30 Å), and Knudsen diffusion (<0.1 μm)	Brittle Expensive Difficulty in scale up
Mixed matrix membranes*	Enhanced mechanical and thermal stability Reduced plasticization Lower energy requirement Compacting at high pressure Surpasses the trade-off between permeability and selectivity Enhanced separation performance over native polymer membranes Separation mechanism: combined polymeric and inorganic membrane principle	Brittle at high fraction of fillers in polymeric matrix Chemical and thermal stabilities depend on the polymeric matrix

**Polymeric membranes: microfiltration, ultrafiltration, nanofiltration, and reverse osmosis filters, which are fabricated only from organic monomers or polymers; ceramic membranes: all filters fabricated from inorganic materials, mixed matrix membranes: are membrane filters fabricated from both organic and inorganic materials.*

Table 1.
Characteristics of different membranes [95] (with permission from publisher).

as a result of defensive system activations. Currently, medium cut-off membranes (60 kDa) are candidates of higher performance with acceptable clearance and low nutrient loss [73, 102]. After many years of development, zwitterionized membranes are most recent generation of hemocompatible dialyzers [96–99].

Rather than FO applications in food industries (as previously mentioned early in the same chapter), the area takes advantages of several other membrane-based processes. Main known applications are beer, beverage and juice concentrations [103–105], and protein recovery from waste streams [104, 106]. More importantly, justification of minerals in dairy streams (milk) to offer value-added products is an interesting application of membranes in food industry [107]. Protein purification (more specifically whey) was conventionally performed by chromatography-based processes. Membrane separation technologies, however, are out weighting those industrial processes due to higher yield and lower energy consumptions [108]. Since nutrition substances own molecular weight and size with different ranges, various membrane processes with different pore size distributions are applied for each specific separation, concentration, or recovery target [109]. Since the technology is one of the main ones in food industries for at least two decades, many integrated processes are now being used for better productions, such as enzymatic hydrolysis ultrafiltration [110]. While the applications might differ from what academic areas have gone through for desalination and water treatment, barriers and accordingly research targets are similar. These include antifouling and antibacterial membrane surfaces, narrow molecular weight cut-off and pore size distribution for higher separation efficiencies, and more stable membranes regarding to their structural and mechanical properties [111–114].

2. Outlook

For past few decades, different aspects of membrane technology application have grown to different extents. The most significant application share of the technology is devoted to water treatment, to both pre- and posttreatments, water desalination, and wastewater treatment. Different aspects of these processes, however, are still being intensively worked on to enhance the economic aspects to minimize the power consumption and environmental aspects (controlling brained streams side effects) of water treatment. Other areas such as cosmetics, pharmaceutical, fuel processing, and production and food industries are all taking benefits from various range of membrane processes. Yet, as the applications are more limited and the processes are fairly complicated, the growth rate is not comparable to water treatment industry. More specific application of thin-film filters in association with biomedical areas (artificial organs) are also experiencing continuous improvements. This is while the issues in these specific areas are focused more on hemocompatibility, biocompatibility, and life-sustaining ability of the technologies rather than on the financial aspects.

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