We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Introductory Chapter: An Overview of Recent Advances in Membrane Technologies

Arash Mollahosseini and Amira Abdelrasoul

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 on 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 matrix 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.

Author details

Arash Mollahosseini¹ and Amira Abdelrasoul^{1,2*}

1 Department of Chemical and Biological Engineering, Faculty of Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

2 Division of Biomedical Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

*Address all correspondence to: amira.abdelrasoul@usask.ca

IntechOpen

© 2020 The Author(s). Licensee IntechOpen. Distributed under the terms of the Creative Commons Attribution - NonCommercial 4.0 License (<https://creativecommons.org/licenses/by-nc/4.0/>), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited.

References

- [1] Vahid HD et al. An investigation into the qualitative and quantitative effects of climate change on rivers in Iran. *International Journal of Review in Life Sciences*. 2016;**6**(2):6-13
- [2] Jury WA, Vaux HJ. The emerging global water crisis: Managing scarcity and conflict between water users. *Advances in Agronomy*. 2007;**95**:1-76
- [3] Reza Balali M, Keulartz J, Korthals M. Reflexive water management in arid regions: The case of Iran. *Environmental Values*. 2009;**18**(1):91-112
- [4] Hameeteman E. Future water (In) security: Facts, figures, and predictions. *Global Water Institute*. 2013;**(1)**:1-16
- [5] Gude VG. Energy consumption and recovery in reverse osmosis. *Desalination and Water Treatment*. 2011;**36**(1-3):239-260
- [6] Stover RL. Seawater reverse osmosis with isobaric energy recovery devices. *Desalination*. 2007;**203**(1-3):168-175
- [7] Pinto FS, Marques RC. Desalination projects economic feasibility: A standardization of cost determinants. *Renewable and Sustainable Energy Reviews*. 2017;**78**:904-915
- [8] Luo T, Young R, Reig P. Aqueduct Projected Water Stress Country Rankings. Technical Note; 2015
- [9] Abdelrasoul A, Doan H, Lohi A. Fouling in membrane filtration and remediation methods. In: *Mass Transfer-Advances in Sustainable Energy and Environment Oriented Numerical Modeling*. United Kingdom: IntechOpen; 2013
- [10] Abdelrasoul A, Doan H, Lohi A. A mechanistic model for ultrafiltration membrane fouling by latex. *Journal of Membrane Science*. 2013;**433**:88-99
- [11] Mollahosseini A, Rahimpour A. A new concept in polymeric thin-film composite nanofiltration membranes with antibacterial properties. *Biofouling*. 2013;**29**(5):537-548
- [12] Maddah H, Chogle A. Biofouling in reverse osmosis: Phenomena, monitoring, controlling and remediation. *Applied Water Science*. 2017;**7**(6):2637-2651
- [13] Komlenic R. Rethinking the causes of membrane biofouling. *Filtration and Separation*. 2010;**47**(5):26-28
- [14] Abdelrasoul A, Doan H, Lohi A. Novel desalination RO membranes. In: *Biomimetic and Bioinspired Membranes for New Frontiers in Sustainable Water Treatment Technology*. United Kingdom: IntechOpen; 2017
- [15] Abdelrasoul A, Doan H, Lohi A. Development of conventional RO membranes. In: *Biomimetic and Bioinspired Membranes for New Frontiers in Sustainable Water Treatment Technology*. IntechOpen; 2017
- [16] Abdelrasoul A, Doan H, Lohi A. Sustainable water technology and water-energy nexus. In: *Biomimetic and Bioinspired Membranes for New Frontiers in Sustainable Water Treatment Technology*. United Kingdom: IntechOpen; 2017
- [17] Chun Y et al. A short review of membrane fouling in forward osmosis processes. *Membranes*. 2017;**7**(2):30
- [18] Li Z et al. Direct and indirect seawater desalination by forward osmosis. In: *Membrane-Based Salinity Gradient Processes for Water Treatment and Power Generation*. Netherlands: Elsevier; 2018. pp. 245-272
- [19] Blandin G et al. Efficiently combining water reuse and desalination

through forward osmosis—Reverse osmosis (FO-RO) hybrids: A critical review. *Membranes*. 2016;**6**(3):37

[20] Cath TY, Childress AE, Elimelech M. Forward osmosis: Principles, applications, and recent developments. *Journal of Membrane Science*. 2006;**281**(1-2):70-87

[21] Chung T-S et al. Forward osmosis processes: Yesterday, today and tomorrow. *Desalination*. 2012;**287**:78-81

[22] Shaffer DL et al. Forward osmosis: Where are we now? *Desalination*. 2015;**356**:271-284

[23] Abdelrasoul A et al. Fouling in forward osmosis membranes: Mechanisms, control, and challenges. In: *Osmotically Driven Membrane Processes-Approach, Development and Current Status*. InTechOpen; 2018

[24] McGovern RK. On the potential of forward osmosis to energetically outperform reverse osmosis desalination. *Journal of Membrane Science*. 2014;**469**:245-250

[25] Phuntsho S et al. Osmotic equilibrium in the forward osmosis process: Modelling, experiments and implications for process performance. *Journal of Membrane Science*. 2014;**453**:240-252

[26] Alsvik I, Hägg M-B. Pressure retarded osmosis and forward osmosis membranes: Materials and methods. *Polymers*. 2013;**5**(1):303-327

[27] Akther N et al. Recent advancements in forward osmosis desalination: A review. *Chemical Engineering Journal*. 2015;**281**:502-522

[28] Qin J-J, Lay WCL, Kekre KA. Recent developments and future challenges of forward osmosis for desalination:

A review. *Desalination and Water Treatment*. 2012;**39**(1-3):123-136

[29] Zhao S et al. Recent developments in forward osmosis: Opportunities and challenges. *Journal of Membrane Science*. 2012;**396**:1-21

[30] Qasim M et al. Water desalination by forward (direct) osmosis phenomenon: A comprehensive review. *Desalination*. 2015;**374**:47-69

[31] Mollahosseini A. Recent advances in thin film composites membranes for brackish groundwater treatment with critical focus on Saskatchewan water sources. *Journal of Environmental Sciences*. 2019;**(18)**:181-194

[32] Peñate B, García-Rodríguez L. Energy optimisation of existing SWRO (seawater reverse osmosis) plants with ERT (energy recovery turbines): Technical and thermoeconomic assessment. *Energy*. 2011;**36**(1):613-626

[33] Mollahosseini A et al. Renewable energy-driven desalination opportunities—A case study. *Journal of Environmental Management*. 2019;**239**:187-197

[34] Mollahosseini A et al. Renewable energy management and market in Iran: A holistic review on current state and future demands. *Renewable and Sustainable Energy Reviews*. 2017;**80**:774-788

[35] Gude VG, Nirmalakhandan N, Deng S. Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews*. 2010;**14**(9):2641-2654

[36] Subramani A, Jacangelo JG. Emerging desalination technologies for water treatment: A critical review. *Water Research*. 2015;**75**:164-187

[37] McCutcheon JR, McGinnis RL, Elimelech M. A novel ammonia—Carbon

dioxide forward (direct) osmosis desalination process. *Desalination*. 2005;**174**(1):1-11

[38] Nicoll PG, Thompson NA, Bedford MR. Manipulated osmosis applied to evaporative cooling make-up water—revolutionary technology. In: *International Desalination Association World Congress; Perth, Western Australia; 2011*

[39] McGinnis RL, Elimelech M. *Global Challenges in Energy and Water Supply: The Promise of Engineered Osmosis*. United States: ACS Publications; 2008

[40] Moody C, Kessler J. Forward osmosis extractors. *Desalination*. 1976;**18**(3):283-295

[41] Thompson NA, Nicoll PG. Forward osmosis desalination: A commercial reality. In: *IDA World Congress—Perth Convention and Exhibition Centre (PCEC); Perth, Western Australia; 2011*

[42] Van der Bruggen B, Luis P. Forward osmosis: Understanding the hype. *Reviews in Chemical Engineering*. 2015;**31**(1):1-12

[43] Veerapaneni S et al. *Desalination Facility Design and Operation for Maximum Efficiency*. Denver: Water Research Foundation; 2011

[44] Chung TS et al. What is next for forward osmosis (FO) and pressure retarded osmosis (PRO). *Separation and Purification Technology*. 2015;**156**:856-860

[45] Ma J et al. Organic matter recovery from municipal wastewater by using dynamic membrane separation process. *Chemical Engineering Journal*. 2013;**219**:190-199

[46] Wintgens T et al. The role of membrane processes in municipal wastewater reclamation and reuse. *Desalination*. 2005;**178**(1-3):1-11

[47] Kovalova L et al. Hospital wastewater treatment by membrane bioreactor: Performance and efficiency for organic micropollutant elimination. *Environmental Science and Technology*. 2012;**46**(3):1536-1545

[48] Liu Q et al. Application of MBR for hospital wastewater treatment in China. *Desalination*. 2010;**250**(2):605-608

[49] Peng Y. Perspectives on technology for landfill leachate treatment. *Arabian Journal of Chemistry*. 2017;**10**:S2567-S2574

[50] Omar H, Rohani S. Treatment of landfill waste, leachate and landfill gas: A review. *Frontiers of Chemical Science and Engineering*. 2015;**9**(1):15-32

[51] Radjenovic J, Petrovic M, Barceló D. Analysis of pharmaceuticals in wastewater and removal using a membrane bioreactor. *Analytical and Bioanalytical Chemistry*. 2007;**387**(4):1365-1377

[52] Fazal S et al. Membrane separation technology on pharmaceutical wastewater by using MBR (membrane bioreactor). *Journal of Environmental Protection*. 2015;**6**(04):299

[53] Ciardelli G, Corsi L, Marcucci M. Membrane separation for wastewater reuse in the textile industry. *Resources, Conservation and Recycling*. 2001;**31**(2):189-197

[54] Ndiaye P et al. Removal of fluoride from electronic industrial effluent by RO membrane separation. *Desalination*. 2005;**173**(1):25-32

[55] Han G, Wang P, Chung TS. Highly robust thin-film composite pressure retarded osmosis (PRO) hollow fiber membranes with high power densities for renewable salinity-gradient energy generation. *Environmental Science and Technology*. 2013;**47**(14):8070-8077

- [56] Straub AP, Deshmukh A, Elimelech M. Pressure-retarded osmosis for power generation from salinity gradients: Is it viable? *Energy and Environmental Science*. 2016;**9**(1):31-48
- [57] Yoon Y et al. Nanofiltration and ultrafiltration of endocrine disrupting compounds, pharmaceuticals and personal care products. *Journal of Membrane Science*. 2006;**270**(1-2):88-100
- [58] Nghiem LD, Schäfer AI, Elimelech M. Pharmaceutical retention mechanisms by nanofiltration membranes. *Environmental Science and Technology*. 2005;**39**(19):7698-7705
- [59] Koyuncu I et al. Removal of hormones and antibiotics by nanofiltration membranes. *Journal of Membrane Science*. 2008;**309**(1-2):94-101
- [60] Garcia-Castello EM, McCutcheon JR, Elimelech M. Performance evaluation of sucrose concentration using forward osmosis. *Journal of Membrane Science*. 2009;**338**(1-2):61-66
- [61] Garcia-Castello EM, McCutcheon JR. Dewatering press liquor derived from orange production by forward osmosis. *Journal of Membrane Science*. 2011;**372**(1-2):97-101
- [62] Chanukya B, Rastogi NK. Ultrasound assisted forward osmosis concentration of fruit juice and natural colorant. *Ultrasonics Sonochemistry*. 2017;**34**:426-435
- [63] Phuntsho S et al. Fertiliser drawn forward osmosis desalination: The concept, performance and limitations for fertigation. *Reviews in Environmental Science and Bio/Technology*. 2012;**11**(2):147-168
- [64] Minaei S, Haghighi M, Jodeiri N, Abdollahifar M, Ajamein H. Influence of CeO₂ on fuel cell grade hydrogen production from steam reforming of methanol over nanostructured mixed oxides of Cu, Zn and Al synthesized via urea-nitrate combustion method. *Journal of Applied Researches in Chemistry*. 2014;**8**(3):33-44
- [65] Larimi YN et al. Waste polymers recycling in biodiesel as a strategy to simultaneously enhance fuel properties and recycle the waste: Realistic simulation and economical assessment approach. *Biofuels*. 2016;**7**(5):559-570
- [66] Peighambari S, Rowshanzamir S, Amjadi M. Review of the proton exchange membranes for fuel cell applications. *International Journal of Hydrogen Energy*. 2010;**35**(17):9349-9384
- [67] Kim DJ, Jo MJ, Nam SY. A review of polymer-nanocomposite electrolyte membranes for fuel cell application. *Journal of Industrial and Engineering Chemistry*. 2015;**21**:36-52
- [68] Maurya S et al. A review on recent developments of anion exchange membranes for fuel cells and redox flow batteries. *RSC Advances*. 2015;**5**(47):37206-37230
- [69] Atadashi I, Aroua M, Aziz AA. Biodiesel separation and purification: A review. *Renewable Energy*. 2011;**36**(2):437-443
- [70] Bateni H, Saraeian A, Able C. A comprehensive review on biodiesel purification and upgrading. *Biofuel Research Journal*. 2017;**4**(3):668-690
- [71] Alicieo T et al. Membrane ultrafiltration of crude soybean oil. *Desalination*. 2002;**148**(1-3):99-102
- [72] Dubé M, Tremblay A, Liu J. Biodiesel production using a membrane reactor. *Bioresource Technology*. 2007;**98**(3):639-647

- [73] Zahan KA, Kano M. Technological Progress in biodiesel production: An overview on different types of reactors. *Energy Procedia*. 2019;**156**:452-457
- [74] Drioli E, Stankiewicz AI, Macedonio F. Membrane engineering in process intensification—An overview. *Journal of Membrane Science*. 2011;**380**(1-2):1-8
- [75] Stankiewicz A. Reactive separations for process intensification: An industrial perspective. *Chemical Engineering and Processing: Process Intensification*. 2003;**42**(3):137-144
- [76] Drioli E et al. Process intensification strategies and membrane engineering. *Green Chemistry*. 2012;**14**(6):1561-1572
- [77] Sirkar KK, Shanbhag PV, Kovvali AS. Membrane in a reactor: A functional perspective. *Industrial and Engineering Chemistry Research*. 1999;**38**(10):3715-3737
- [78] Maghami M, Abdelrasoul A. Zeolite mixed matrix membranes (Zeolite-Mmms) for sustainable engineering. In: *Zeolites and Their Applications*. United Kingdom: IntechOpen; 2018
- [79] Maghami M, Abdelrasoul A. Zeolites-mixed-matrix nanofiltration membranes for the next generation of water purification. In: *Nanofiltration*. United Kingdom: IntechOpen; 2018
- [80] Mollahosseini A et al. The effect of silver nanoparticle size on performance and antibacteriality of polysulfone ultrafiltration membrane. *Desalination*. 2012;**306**:41-50
- [81] Emadzadeh D et al. A novel thin film nanocomposite reverse osmosis membrane with superior anti-organic fouling affinity for water desalination. *Desalination*. 2015;**368**:106-113
- [82] Rahimpour A et al. Structural and performance properties of UV-assisted TiO₂ deposited nano-composite PVDF/SPES membranes. *Desalination*. 2012;**285**:31-38
- [83] Mollahosseini A, Rahimpour A. Interfacially polymerized thin film nanofiltration membranes on TiO₂ coated polysulfone substrate. *Journal of Industrial and Engineering Chemistry*. 2014;**20**(4):1261-1268
- [84] Rahimpour A et al. Novel functionalized carbon nanotubes for improving the surface properties and performance of polyethersulfone (PES) membrane. *Desalination*. 2012;**286**:99-107
- [85] Bastani D, Esmaeili N, Asadollahi M. Polymeric mixed matrix membranes containing zeolites as a filler for gas separation applications: A review. *Journal of Industrial and Engineering Chemistry*. 2013;**19**(2):375-393
- [86] Lau W et al. A review on polyamide thin film nanocomposite (TFN) membranes: History, applications, challenges and approaches. *Water Research*. 2015;**80**:306-324
- [87] Wang X et al. Preparation and characterization of CA/GO mixed matrix forward osmosis membranes. In: *International Symposium on Mechanical Engineering and Material Science (ismems-16)*. France: Atlantis Press; 2016
- [88] Shen L, Xiong S, Wang Y. Graphene oxide incorporated thin-film composite membranes for forward osmosis applications. *Chemical Engineering Science*. 2016;**143**:194-205
- [89] Choi H-G, Son M, Choi H. Integrating seawater desalination and wastewater reclamation forward osmosis process using thin-film composite mixed matrix membrane with functionalized carbon nanotube

blended polyethersulfone support layer. *Chemosphere*. 2017;**185**:1181-1188

[90] Bakangura E et al. Mixed matrix proton exchange membranes for fuel cells: State of the art and perspectives. *Progress in Polymer Science*. 2016;**57**:103-152

[91] Park MJ et al. Mixed matrix nanofiber as a flow-through membrane adsorber for continuous Li⁺ recovery from seawater. *Journal of Membrane Science*. 2016;**510**:141-154

[92] Samanta HS, Ray SK. Separation of ethanol from water by pervaporation using mixed matrix copolymer membranes. *Separation and Purification Technology*. 2015;**146**:176-186

[93] Thornton AW et al. Feasibility of zeolitic imidazolate framework membranes for clean energy applications. *Energy and Environmental Science*. 2012;**5**(6):7637-7646

[94] Ghalia MA, Abdelrasoul A. Synthesis and characterization of biopolymer-based mixed matrix membranes. In: *Biomass, Biopolymer-Based Materials, and Bioenergy*. Netherlands: Elsevier; 2019. pp. 123-134

[95] Vinoba M et al. Recent progress of fillers in mixed matrix membranes for CO₂ separation: A review. *Separation and Purification Technology*. 2017;**188**:431-450

[96] Sin M-C, Chen S-H, Chang Y. Hemocompatibility of zwitterionic interfaces and membranes. *Polymer Journal*. 2014;**46**(8):436

[97] Zhao Y-H, Wee K-H, Bai R. Highly hydrophilic and low-protein-fouling polypropylene membrane prepared by surface modification with sulfobetaine-based zwitterionic polymer through a combined surface polymerization method. *Journal of Membrane Science*. 2010;**362**(1-2):326-333

[98] Ostuni E et al. A survey of structure– property relationships of surfaces that resist the adsorption of protein. *Langmuir*. 2001;**17**(18):5605-5620

[99] Shen M et al. PEO-like plasma polymerized tetraglyme surface interactions with leukocytes and proteins: In vitro and in vivo studies. *Journal of Biomaterials Science, Polymer Edition*. 2002;**13**(4):367-390

[100] Mrabet B et al. Anti-fouling poly (2-hydroxyethyl methacrylate) surface coatings with specific bacteria recognition capabilities. *Surface Science*. 2009;**603**(16):2422-2429

[101] Yoshikawa C et al. Protein repellency of well-defined, concentrated poly (2-hydroxyethyl methacrylate) brushes by the size-exclusion effect. *Macromolecules*. 2006;**39**(6): 2284-2290

[102] Zweigart C et al. *Medium Cut-off Membranes-Closer to the Natural Kidney Removal Function*. London, England: SAGE Publications Sage UK; 2017

[103] Girard B, Fukumoto L. Membrane processing of fruit juices and beverages: A review. *Critical Reviews in Food Science and Nutrition*. 2000;**40**(2):91-157

[104] Ambrosi A, Cardozo NSM, Tessaro IC. Membrane separation processes for the beer industry: A review and state of the art. *Food and Bioprocess Technology*. 2014;**7**(4):921-936

[105] Ilame SA, Singh SV. Application of membrane separation in fruit and vegetable juice processing: A review. *Critical Reviews in Food Science and Nutrition*. 2015;**55**(7):964-987

[106] Chollangi A, Hossain MM. Separation of proteins and lactose from dairy wastewater. *Chemical Engineering*

and Processing: Process Intensification. 2007;**46**(5):398-404

membranes. Journal of Membrane Science. 2008;**311**(1-2):349-359

[107] Marella C, Muthukumarappan K, Metzger L. Application of membrane separation technology for developing novel dairy food ingredients. Journal of Food Processing and Technology. 2013;**4**(269):10.4172

[108] Agüero R et al. Membrane processes for whey proteins separation and purification. A review. Current Organic Chemistry. 2017;**21**(17):1740-1752

[109] Kumar P et al. Perspective of membrane technology in dairy industry: A review. Asian-Australasian Journal of Animal Sciences. 2013;**26**(9):1347

[110] Daufin G et al. Recent and emerging applications of membrane processes in the food and dairy industry. Food and Bioproducts Processing. 2001;**79**(2):89-102

[111] Rahimpour A et al. Preparation and characterization of modified nanoporous PVDF membrane with high antifouling property using UV photografting. Applied Surface Science. 2009;**255**(16):7455-7461

[112] Yu L et al. Preparation and characterization of HPEI-GO/PES ultrafiltration membrane with antifouling and antibacterial properties. Journal of Membrane Science. 2013;**447**:452-462

[113] Rahimpour A, Madaeni SS. Polyethersulfone (PES)/cellulose acetate phthalate (CAP) blend ultrafiltration membranes: Preparation, morphology, performance and antifouling properties. Journal of Membrane Science. 2007;**305**(1-2):299-312

[114] Rahimpour A, Madaeni S, Mehdipour-Ataei S. Synthesis of a novel poly (amide-imide) (PAI) and preparation and characterization of PAI blended polyethersulfone (PES)