Chapter 3

Microfiltration and Ultrafiltration Membranes for Water Purification

Priya Banerjee^{1*}, Sandipan Bhattacharya², Rasel Das^{3,4}, Papita Das^{2,5},
Aniruddha Mukhopadhyay⁶

¹ Department of Environmental Studies, Centre for Distance and Online Education, Rabindra Bharati University, Kolkata 700091, India

² Department of Chemical Engineering, Jadavpur University, Kolkata 700032, India

³ Department of Biochemistry and Biotechnology, University of Science and Technology Chittagong, Foy's lake-4202, Chattogram, Bangladesh

⁴ Department of Chemistry, Stony Brook University, Stony Brook, NY 11794, United States

⁵ School of Advanced Studies in Industrial Pollution Control Engineering, Jadavpur University, Kolkata 700032, India

⁶ Department of Environmental Science, University of Calcutta, Kolkata 700019, India

*prya_bnrje@yahoo.com

Abstract

Random and rampant urbanization have rendered one third of the global population vulnerable to water scarcity. For mitigating this problem, membrane technology has been widely investigated for desalination as well as reuse and reclamation of wastewater. Polymeric membranes have reportedly displayed significantly lower consumption of energy with potential self-cleansing and antifouling. Application of microporous and ultraporous polymeric membranes for water purification has been vividly discussed herein. The diverse facets of water treatment technologies using polymeric membranes compiled herein will facilitate all potential readers like academicians, environmentalists, industrialists and membrane technologists, and to address the water scarcity challenges of our society.

Keywords

Polymers, Biopolymers, Microfiltration, Ultrafiltration, Emerging Pollutants, Desalination

Contents

Microfiltration and Ultrafiltration Membranes for Water Purification.....33

1. Introduction.....	35
2. Polymers for membrane preparation	37
3. Polymeric membrane for microfiltration (MF).....	39
4. Polymeric membranes for ultrafiltration (UF).....	40
4.1 Incorporation of TiO ₂ NPs into polysulfone (PSF)	40
4.2 Integration of mesoporous silica particles (MSP-1) within polysulfone (PSF)	41
4.3 Integration of silica and zinc oxide (ZnO) NPs within polyvinyl chloride (PVC) and poly(methacrylic acid) (PMAA) matrices.....	41
4.4 Polyethersulfone (PES).....	42
4.5 Polyvinylidene fluoride (PVDF).....	43
5. Biopolymer based membranes	44
5.1 Biopolymers obtained via bacterial fermentation.....	45
5.1.1 Polylactic acid (PLA)	45
5.1.2 Polyhydroxyalkanoates (PHA)	46
5.1.3 Poly(butylene succinate) (PBS).....	46
5.2 Biopolymers derived from vegetable sources	47
5.2.1 Cellulose-based polymers.....	47
5.2.2 Alginate.....	48
5.2.3 Starch	49
5.3 Biopolymers derived from animal sources.....	49
5.3.1 Chitosan (CS).....	49
5.3.2 Collagen and sericin	50
6. Factors affecting membrane efficacy.....	51
6.1 Operating condition	51
6.1.1 Temperature	51
6.1.2 Operating pressure	51
6.1.3 Flow rate	51

6.2	Membrane characteristics	51
6.2.1	Feed characteristics.....	52
6.2.2	Fouling.....	52
6.3	Pretreatment of membrane.....	53
7.	Application of polymeric membranes for water purification	53
	Conclusion.....	57
	References	58

1. Introduction

In the last century, water consumption rates had nearly doubled in comparison to the growth of population, thereby making water scarcity a reality for the vast majority of population of the 21st century. The Earth has limited supplies of fresh water which are being rapidly depleted every day. According to a study conducted by the United Nations, two third of the global population of the world will be experiencing severe water crisis by 2025 [1]. The rapid and unplanned urbanization, which is rampant nowadays, often results in the destruction of adjacent water bodies, further worsening the water crisis situation. Other than manmade causes, climate change induced by global warming and other weather extremities have led to the rising of the sea level, causing submergence of land and freshwater resources and increased rates of evaporation. These events have collectively increased the salinity of both fresh and marine water resources thereby resulting in a sharp decline in the availability of freshwater resources. Also, due to the complexities associated with the monitoring and regulation of the components responsible for water pollution, there is a lack of effective water treatment technologies. This in turn results in a dearth of clean potable water for the rapidly growing population [2]. This impending scarcity of water is expected to affect all the aspects of social progress including the health, economy and sustainable development of the country or region under concern. Thus, in keeping with the requirements of the present times, it has been considered imperative to determine economic and efficient technologies for the purpose of treating wastewater in compliance with the regulatory guidelines for reuse in domestic and industrial sectors with the aim of restoring safe environment.

Generally, water treatment is carried out as primary secondary and tertiary processes which include methods of physical separation, microbial treatments and chemical treatments like electrocoagulation, photocatalysis, adsorption, etc. respectively [3].

Nonetheless, majority of the conventional technologies of water treatment has resulted in inefficient removal of pollutants from different streams of wastewater [3].

The drawbacks of each process of wastewater treatment have been shown in Fig. 1. Out of all the water treatment processes discussed so far, water treatment by membrane technologies have been widely applied owing to its chemical and thermal inertness and expedient techniques of regeneration. Due to the prospect of performing water purification up to the level of ionic filtration and many other added advantages, membrane filtration has emerged as one of the more popular methods of water treatment practiced in recent times. As membranes only permit the passage of aqueous solvents, membrane filtration efficiently separates different particles, solutes, gases and other pollutants present in effluents.

Figure 1. Schematic depiction of major limitations of conventional processes of water purification (adapted from Das et al. [3]).

The membrane separation process that are generally applied for wastewater treatment include distillation, different types of dialysis, micro (MF), ultra (UF) and nano (NF)

filtration, osmosis (reverse (RO) and forward (FO)) and vacuum filtration. MF, UF, NF and RO are pressure driven processes that are widely applied for water treatment carried out on large scale. However, the high energy requirement of these processes is a drawback for their wide scale commercial application. Other than that, the precipitation of the pollutants results in the fouling and pore blockage of the membranes, thus reducing their efficiency and shortening their lifetime [3]. The membranes also need periodic cleaning and substitution as they are incapable of self-cleaning.

As per recent studies, the FO membranes used for capacitive deionization and distillation are capable of efficient desalination but are not obtainable for commercial scale applications [4]. Due to these limitations, the scientists are impelled to find alternative technologies for cost effective treatment of wastewater. The success in the field of adsorptive removal of water pollutants has prompted the researchers to explore different biomaterials for the purpose of synthesizing the membranes. Biomaterials generally have low carbon footprint and can be used individually or in the form of composites for manufacturing the membranes. Composites are considered to be advantageous over individual membranes as because on one hand they possess the favorable properties of their parent components and on the other hand they are able to overcome limitations of their individual components due to their composite nature. With reference to these points, inexpensive and easily available biopolymers like polysaccharides, lignin, alginate etc. can be considered as ideal components for the membrane-based separation of pollutants [5]. Furthermore, the rapid advancement in the fields of nanoscience and nanotechnology has prompted the researchers to develop highly functionalized nanocomposite with biomaterials as their base for the removal of emerging pollutants via adsorption. Different polymers reported for synthesis of MF and UF membranes and subsequent implementation of these membranes for water purification and desalination have been extensively reviewed herein.

2. Polymers for membrane preparation

A polymer is substance or material consisting of repeating subunits of very large molecules or macromolecules or a mixture of macromolecules having a molecular weight higher than 1000 gmol^{-1} [6]. Polymers are assembled in the form of chain(s) containing thousands to millions of repeating units of monomers bearing positive, negative or both charges. The polymers chains may be 400 to 8000 ft in length [6]. A polymer may be cationic, anionic, amphoteric or nonionic according to the charge of its monomers [6]. The overall charge density of the polymer depends upon the charge of its monomers and is usually expressed as percentage. Polymers may be classified as linear, branched or cross linked (as shown in Fig. 2) on the basis of its chain orientation.

Polymers can be classified into biopolymers or chemical polymers on the basis of their parent material. Some of the chemical polymers that have been widely mentioned in recent studies include cellulose acetate (CA), polyacrylonitrile, polyaniline nanoparticles (NPs), poly(arylene ether ketone), polyamide, poly(etherimide), polyethersulfone (PES), polysulfone, polyethylene glycol (PEG), polyimide, poly(methacrylic acid), polyvinyl alcohol (PVA), polyvinyl chloride, and polyvinylidene fluoride (PVDF) [6]. Biopolymers like cellulose, chitin, chitosan etc. have been widely used for membrane synthesis. A large number of studies conducted in recent times have emphasized on improvement of polymeric membranes in terms of antifouling properties, chemical resistance, energy consumption, salt rejection and water flux, and of by blending and surface modification.

Figure 2. Classification of polymers (adapted from Das [6])

Polymeric membranes are cheaper compared to those made from inorganic materials and ceramics [7]. Also, a higher level of water production can be achieved through polymeric membranes. Polymeric membranes easily fabricated and conveniently aligned as hollow fiber and spiral wounds for achieving optimum efficiency [7,8]. This chapter reviews the application of polymeric materials for water treatment and desalination reported in recent studies. More precisely, the recent developments in the synthesis of polymeric membrane for MF and UF have been discussed herein. The selection of an appropriate polymer for filtration is critical as it is responsible for the permeate quality and cost incurred by the concerned process. Thus, selection of an appropriate polymer ensures the avoidance of

issues like frequent replacement of membranes and unjustified consumption of energy. The current limitations of newly synthesized polymers have also been discussed in this chapter.

3. Polymeric membrane for microfiltration (MF)

MF membranes have been mainly applied for wastewater treatment processes, membrane distillation (MD) and membrane bioreactors (MBRs) [6,9,10,11,12,13]. Industrial and domestic effluents contain toxic organic pollutants (like pharmaceuticals) which exert detrimental impacts on the aquatic species and the general environment alike. Modern technologies like advanced oxidation processes (AOP) have demonstrated high efficiency for the purpose of treating recalcitrant wastewater [6]. Photocatalysis by TiO_2 is one the most renowned AOPs capable of completely degrading the organic molecules [6]. The direct integration of TiO_2 nanoparticles within PES and PVDF MF membranes has been found to enhance the efficiency of the same [6]. Though addition of TiO_2 decreased membrane porosity, it enhanced membrane efficiency for degrading different pollutants like dyes, pharmaceuticals, pesticides, etc.

MD is a temperature driven process used for separating pollutants and water molecules by passing the fluid through a porous membrane [10,14]. MD is carried out on the basis of vapor permeation. Therefore, MD is carried out with hydrophobic membranes. MD is driven by the difference of vapor pressure developing across a hydrophobic membrane. However even though MD is conveniently implemented, it has still not gained wide scale industrial application due to several limitations like fouling and declining flux that are most prominent and difficult to address. However, direct contact MD (DCMD) membranes have recently exhibited an increase in flux when treated by tetrafluoromethane (CF_4) plasma surface modification [10,14]. The overall flux of the plasma modified membrane exceeded that of the untreated membranes. CF_4 plasma treatment converted the PVDF membranes to super hydrophobic plasma membranes having increased flux and greater capacity for salt rejection [10,14].

Membrane bioreactor (MBR) has recently gained widescale popularity as a mode of water treatment because of its ability to produce permeates of high quality, noticeable decrease in the generation of sludge, ability to control solids and reducing the operational costs [15,16]. Among its many advantages, a significant disadvantage of MBR operation is membrane fouling [17,18]. In an effort to overcome this, MF membranes are being prepared with GO to produce membranes having antifouling properties [6]. This development is influenced by the unique hydrophilicity and large negative zeta potential of GO which can be ascribed to functional group present on GO surfaces. These properties of GO facilitate permeation of water through the membrane and reduces

biofouling [6]. Higher percentage of GO in the membrane increased the negative zeta potential induced by GO, decreased the thickness of the biofilm layer formed on the GO incorporated membrane and significantly increased pure water flux [6]. The high energy demand incurred for avoiding fouling of membrane is an unintended disadvantage of the MBR technology. Thus, in order to alleviate this problem, investigations on osmotic MBRs (OMBRs) have escalated recently [19,20,21]. The OMBRs, are driven by the osmotic pressure gradient formed between the feed and draw sectors of the membrane. Nevertheless, in contrast to conventional MBR, which has a microporous membrane, OMBRs possess a high rejection semipermeable membrane. In comparison to other membrane technologies, OMBRs have lower fouling, but still experience membrane fouling. The increased salinity and the resultant accumulation of salt, the interaction between organic foulants and inorganic ions and the gradient of low soluble salts formed under high ionic strength might give rise to more complicated fouling scenarios [22]. However, the compaction of foulants is milder in OMBRs due to the absence of hydraulic pressure. Hence it may be considered that fouling is effectively reduced in presence of hydrodynamic shear.

4. Polymeric membranes for ultrafiltration (UF)

Polymeric materials have been widely used for the preparation of UF, PS and PES membranes due to their robust mechanical properties, a very wide operational range of pH and high chemical stability [23,24,25,26,27,28,29]. However, their implementation in the area of water purification is restricted due to their hydrophobic nature which results in reduced membrane permeability. Recent studies have reportedly used naturally hydrophobic polymers like PMAA, PVC and PVDF for fabrication of UF membranes [30,31,32,33,34,35]. Membrane hydrophobicity poses many problems like decline in water flux during an ongoing process as a result of accumulation of organic compounds. These organic compounds in turn facilitate the attachment and growth of microorganisms on the membrane surface causing membrane fouling and resultant membrane failure. Therefore, necessary modifications are needed to be made in the polymeric materials in order to improve their ability for greater performance in the water treatment methods. These modifications increase membrane in turn reducing the probability of membrane fouling in case of liquid-based filtration.

4.1 Incorporation of TiO₂ NPs into polysulfone (PSF)

For increasing the hydrophilicity of the UF membranes, hydrophilic materials like NPs and amphiphilic copolymers are incorporated into the membranes by blending and surface modification [6]. According to recent studies, incorporation of modified TiO₂

particles in hybrid PSF membranes increase the hydrophilicity of the latter [6,7]. Polymer chains of (2-hydroxyethyl methacrylate) (P(HEMA)) on TiO₂ NPs were grafted via atom transfer radical polymerization for synthesis of these membranes. The reason behind the impregnation of PSF membranes with the modified TiO₂ NPs is enhancing the membrane performance, controlling the NP agglomeration on membrane surface and preventing the NP leakage from membrane during the process of filtration. Modified TiO₂ reportedly demonstrates better dispersibility within the polymer than unmodified TiO₂ [6]. TiO₂-HEMA modified PSF membrane displayed enhanced hydrophilicity, greater water flux and superior antifouling property in comparison with PSF membrane impregnated with unmodified TiO₂ particles.

4.2 Integration of mesoporous silica particles (MSP-1) within polysulfone (PSF)

Addition of inorganic particles into the casting mixture of the membrane before phase inversion is a simple and effective method by which additional particle-based functionalities can be incorporated into a membrane. As such this method of membrane modification is widely studied [36,37]. With the aim of improving the properties of the PSF membrane they are impregnated with surfactant templated MSP-1 with or without PEG as a molecular porogen [6]. The terminal silanol (Si-OH) groups present on the pore walls and external surfaces of MSP-1 particles increased the hydrophilicity of the PSF membranes. Integration of MSP-1 and PEG modified the archetypal morphology of the phase inversion PSF membrane. The PSF-MSP membranes demonstrate mechanical properties and they are equivalent to those sans MSP. Porogen free membranes made from casting solutions having low polymer content demonstrated significantly higher permeate flux when modified with MSP-1. A 5 % increase in the MSP -1 loading to the membrane has a highly damaging effect on the flux, whereas a 10 % increase yielded permeate flux equivalent to MSP-free control. Nonetheless, the inclusion of PEG porogen in the casting mixture yielded no statistically significant changes in terms of flux or rejection. The composite membrane also exhibited superior dextran rejection than MSP-free membrane. Moreover, the composite membrane exhibited lower decline of flux and increased rejection in comparison with its MSP free membranes during the fouling tests carried out with humic acid solutions.

4.3 Integration of silica and zinc oxide (ZnO) NPs within polyvinyl chloride (PVC) and poly(methacrylic acid) (PMAA) matrices

Recent studies have reported an increase in hydrophilicity of PVC UF membranes as a result of integration of NPs into PVC matrices [39]. Five PVC membranes were fabricated with variable ZnO percentages by phase inversion method using water (coagulant) and PEG (pore forming additive). The membranes impregnated with ZnO

NPs exhibited higher hydrophilicity in comparison to pristine PVC membrane. Results revealed an increase in water flux with a corresponding increase in ZnO loading up to 3 wt %. However, any further increase in ZnO percentages resulted in clustering of ZnO particles on the membrane surface leading to a decline of water flux (Fig. 3). Increase in ZnO loadings (upto 3 wt%) also lead to a parallel increase in porosity. However, a further increase in ZnO percentage resulted in a decline of membrane porosity. Pristine PVC membranes recovered 69 % of water flux while membranes impregnated with ZnO (3 wt %) recovered 92 % water flux post bovine serum albumin (BSA) permeation. Impregnation of PMAA with NPs has also been examined recently for enhancing PMAA based UF membrane efficiency. Grafting of superhydrophilic silica NPs into PMAA membrane matrices resulted in an increase in membrane wettability [6].

Figure 3. Agglomeration of ZnO NPs in PVC-ZnO casting solution as revealed by Energy dispersive X-ray (EDAX) spectroscopy. Both top and bottom panel have scale of 70 μ m (Adapted from Rabiee et al. [39]).

4.4 Polyethersulfone (PES)

PES has been frequently utilized for synthesis of UF membranes [6]. In a recent study, carboxylic and amine group bearing mesostructured silica particles were incorporated into PES membranes for improving hydrophilicity of the latter [40]. Integration of ordered mesoporous silica particles significantly modified membrane pore size, porosity

and morphology and also increased membrane hydrophilicity. Enhanced membrane hydrophilicity and surface porosity in turn increased water permeation. The antifouling property of the membrane also increased due to this modification, especially against irreversible fouling without any negative effect against the protein rejection potential of the membrane. The modified membrane yielded stable permeation performance throughout repeated stability tests. Another recent study has proposed polyether sulfone amide (PESA), a PES based hydrophilic polymer for membrane synthesis [41]. PESA was subjected to interfacial polymerization using gallic acid (GA) and 3,5-diaminobenzoic acid (DBA). PESA membranes demonstrated more hydrophilicity in comparison to pure PES membrane. Functionalization of PESA membranes using DBA and GA made the same more hydrophilic. PESA and functionalized PESA membranes possessed greater roughness than pure PES membranes. Moreover, PESA membranes were also more efficient than PES membranes in terms of antifouling properties, pure water flux and humic acid rejection [41].

Incorporation of polyaniline (PANI) NPs was found to enhance the hydrophilicity of PES UF membranes [6]. Incorporation of PANI NPs also enhanced the fouling resistance, flux recovery, pollutant rejection and antimicrobial potential of the PES membranes. Moreover, PANI synthesized indigenously by authors was found to yield superior membrane properties in comparison to commercial PANI. PES UF membranes can also be modified using polyethylene glycol and silver NPs [42]. For some separation process, hollow polymeric membranes were favored due to convenient module fabrication, excellent flexibility, high surface area and self-mechanical support [42]. The modified membrane demonstrated enhanced antimicrobial properties, hydrophilicity and water flux. Dextran-grafted halloysite nanotubes (HNTs) have also been used for modification of PES UF membranes [43]. HNT modified membranes reportedly demonstrate enhanced antifouling property, hydrophilicity and water flux in comparison to unmodified PES membranes [43]. Moreover, HNT modified membranes were found to exhibit slightly lower porosity but greater pore size in comparison to that of PES membranes.

4.5 Polyvinylidene fluoride (PVDF)

PVDF also enhances membrane hydrophilicity. PVDF UF membranes have also been modified with dopamine solution via self-polymerization [44]. Any unreacted polydopamine was rinsed off with water. The dopamine coated PVDF membrane was further dipped in a TiO₂ NP solution whereby Dopamine expedited the uniform distribution and attachment and prevented agglomeration of TiO₂ NPs on PVDF membrane surface. The notable reduction in the water contact angle of the membrane denoted an increase in its hydrophilicity due to its modification. Both the pure water flux and the BSA rejection capacity of the membrane increased significantly due to the

modifications. A significant improvement of antifouling properties of the membrane was indicated by the enhanced flux recovery ratio ($> 90\%$) and reduced irreversible fouling ratio [44].

4.6 Poly(arylene ether ketone) (PAEK) and poly(ether imide) (PEI)

PAEK and PEI have also been investigated for preparation of UF membranes [45, 46]. PAEK membranes functionalized with carboxylic acid groups (PAEK-COOH) have been found to be more hydrophilic than traditional PAEK membranes [46]. PAEK-COOH was then used for the synthesis of tight UF membranes via the process of nonsolvent induced phase inversion. The resultant membrane displayed high water permeation flux and dye rejection. The membrane was also thermally stable and was suitable for high temperature filtration application. These membranes exhibited a flux recovery rate of 91.5% for BSA. They also demonstrated impressive antifouling potential. The adsorption rate of these membranes was found to be lower than 5.0 % for all tested dyes.

In a recent study, PEI was blended with N-phthaloylated chitosan (NPHC) in order to enhance the hydrophilicity and antifouling properties of the resultant UF membranes [45]. The modified membranes also demonstrated higher surface roughness as compared with the unmodified membranes. Pure water and permeate flux as well as heavy metal ion separation, of the PEI–NPHC membranes were increased with a corresponding increase in NPHC concentration of blended membranes. An NPHC concentration of 2.0 wt % yielded maximum flux recovery [45].

5. Biopolymer based membranes

Biopolymers are widely synthesized from vegetable (alginate, cellulose, polyisoprene, starch, etc.) or animal (polybutylene succinate, polyhydroxyalcanoates, polylactic acid, etc.) derivatives [47]. Biopolymers like chitin, chitosan, collagen and sericin are obtained via bacterial fermentation [47]. The application of biopolymers for the “green” synthesis of membranes have been well studied and well documented in scientific literature. However, utilization of biopolymers on a commercial scale is still a challenge. The advantages of using bio-based solvents include low consumption of energy sources, biodegradability and reduced toxicity [48]. Nevertheless, the cost of replacing the standard technology and the corresponding production lines in use for green synthesis of plastics from petrochemical compounds are extremely high. Moreover, the existing rate of biopolymer production is insufficient for meeting the large requirement of the membrane industry for the same. However, synthetic polymers, synthesized from petroleum materials, cause a massive surge in pollution of the environment which in turn prompts the researchers to actively pursue an interest in biopolymer-based membranes

due to their sustainable nature. Traditional plastics generally require an immensely long time to degrade, resulting in secondary pollution and high cost of treatment. Therefore, in order to solve these problems, an effort must be taken to substitute petroleum-based membrane with more biocompatible alternatives. Natural materials can be used as efficient substitutes of petroleum-based compounds. These materials occur in abundance and are renewable. Further research is required for harnessing the true potential of these resources. Few such biopolymers investigated for membrane synthesis has been discussed as follows.

5.1 Biopolymers obtained via bacterial fermentation

5.1.1 Polylactic acid (PLA)

PLA is a widely investigated bioplastic with commercial applications. This biodegradable polyester is largely derived from lactic acid. The amorphous and crystalline structure of PLA is due to the result of copolymerization of L and D-lactic acid which impacts the properties of resultant PLA [49]. PLA could be synthesized by ring opening polymerization of cyclic lactide monomer or direct polycondensation of hydroxyl acid. The utilization of PLA as a constituent for the synthesis of membrane synthesis is a comparatively recent idea. PLA-MF membranes prepared by thermally induced phase separation (TIPS) had pore sizes ranging from 0.6 to 4.4 μm [47]. The membrane performance was tested in terms of bacteria cell retention and protein molecule permeation [50]. The synthesis and drying of the polymer solution prior to quenching caused variations in the structures of pores present near the surface of the membranes which in turn enhanced bacterial cell rejection by the membrane. These membranes are synthesized from recyclable and compostable polymers. Hence, they are considered as justifiable alternatives to conventional synthetic polymer membranes usually employed for water treatment. Porous PLA membranes with PEG as a pore former were produced by Chitarattha and Phaechamud [51]. Authors also investigated the effect of non-solvents like ethanol, glycerin and isopropanol on synthesis of membranes in terms of the mechanism of pore formation in the PLA matrices [52]. They successfully tailored the membrane morphology and efficiency as required for the final application of the membranes by altering the production parameters of the same. Interestingly, Moriya et al. [53] exhibited an interesting option for synthesizing PLA having high hydrophilicity by utilizing PEG as a porogen. Modification of poly(ϵ -caprolactone) (PCL) with PLA showed lower membrane resistance towards yeast cells than unmodified ones [47]. Minbu et al. [54] used Tween 80 (surfactant) and 1,4-dioxane (solvent) for synthesis of MF-PLA membranes via the NIPS technique. A recent study proposed the synthesis of porous PLA membranes by hot water droplet induced phase separation [55].

5.1.2 Polyhydroxyalkanoates (PHA)

PHA are linear biopolyesters of 3,4,5 and 6 hydroxyalkanoic acids which are produced from the fermentation of different substrates used as carbon sources by both Gram positive and Gram-negative bacteria. The most well-known polymers of PHA family are polyhydroxybutyrate (PHB) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) [56]. PHB is the most common PHA produced by fermentation by bacteria like *Alcaligenes*, *Azobacter*, *Bacillus* and *Pseudomonas* [47]. PLA and PHBV have been combined in a recently developed procedure to synthesize novel blended membranes [57,58]. The membranes synthesized by the mixture of PLA and PHBV had increased strength and ductility when compared to membranes synthesized from only PHBV. Along with this, the time required for the natural degradation of this hybrid membrane is much shorter when compared to the membranes made from only PHBV [47]. Biodegradable membrane for the purpose of water treatment was synthesized by Keawsupsak et al. [58] by blending PLA with PBAT, PHBV or PBS via non solvent (water) induced phase separation. PHB has restrictive use as a polymer owing to its high crystallinity and brittleness. According to Miguel et al. [47], PHB acts as a high barrier for CO₂ with a good separation of CO₂ from water. Dense PV membranes using PHB was synthesized by Villegas et al. [59, 60] for the separation of methanol/water and methanol/methyl-tert-butyl ether (MTBE) mixtures. In case of both mixtures, PHB membranes offered good structural stability in response to swelling, and yielded high flux as well as moderate selectivity.

5.1.3 Poly(butylene succinate) (PBS)

PBS is obtained as a semi crystalline biopolymer as a result of polymerization of succinic acid and butanediol [47]. Both succinic acid and butanediol are easily synthesized from bio-based renewable resources [47]. Succinic acid is synthesized from microbial fermentation of renewable stocks like glucose and starch. Butanediol may be synthesized via catalytic reduction of succinic acid or direct fermentation of sugar [47]. Esterification of succinic acid and butanediol and subsequent polycondensation of the resultant oligomers lead to the formation of PBS. In recent studies, PBS has been combined with PES and CA for synthesis of blended membranes [61,62,63]. The blended membranes possessed lower crystallinity and demonstrated larger mechanical resistance than unmodified PBS membrane. Moreover, the PES-PBS systems exhibited higher tensile strength and lower membrane crystallinity than CA-PBS systems prepared with equivalent blend ratios. PBS-PES systems were further blended with PEG for the synthesis of membranes having enhanced efficiency for wastewater treatment.

5.2 Biopolymers derived from vegetable sources

5.2.1 Cellulose-based polymers

Cellulose is a polysaccharide synthesized by plants. It is one of the primary polymers present in nature and it is composed of long macromolecular β -D-glucose chains [47]. Cellulose is primarily obtained from lignocellulosic biomass made up of lignin and hemicellulose. Cellulose derivatives are synthesized via different methodologies. Cellulose acetate (CA), for example is generally prepared by treating cellulose with acetic acid in presence of sulfuric acid and acetic anhydride as catalysts. Conversely, hydroxyethyl cellulose (HEC) is prepared by treating alkali modified cellulose with ethylene oxide [64]. One of the first commercially implemented polymeric membranes was prepared in the 1960s using asymmetric CA fabrics [47]. These membranes had high flux and high salt rejection capacity. CA membranes synthesized by the acetyl substitution of cellulose, a naturally abundant polymer, have been utilized widely at the commercial level to control the microorganism load in untreated water subjected to RO and UF [65,47]. CA has been widely synthesized from cotton, recycled paper or wood cellulose [47]. CA membranes have lower aversion to chloride in comparison to PA membranes and have largely replaced the same in desalination processes. CA also has a lower membrane fouling tendency than conventional PA membranes used for water treatment processes [66]. Further investigations on CA could enhance membrane technology and replace traditional synthetic polymers in commercial applications. In order to improve antifouling properties of CA in a sustainable manner, authors have impregnated electrospun CA fiber matrix with chitin nanocrystals [67,68]. As a result of which, the membrane surface became highly hydrophilic thereby reducing the membrane fouling. Previous studies have investigated the effect of PVP addition and alterations in coagulation bath temperature on asymmetric CA membranes synthesis via phase inversion method [47]. According to the results obtained, hydrophilicity and flux of the membranes improved with a corresponding increase in the amount of PVP blended in the membrane. Previous studies have also reported CA-PSF UF membranes prepared via phase inversion [47]. Kanagaraj et al., [69] investigated the antifouling capacity, selectivity and flux of membranes prepared by combining CA with hydrophilic surface modifying macromolecules (SMMs). The resultant membranes displayed better flux recovery and antifouling properties. Varanasi et al [70] synthesized biodegradable UF membranes from *P*-amine-epichlorohydrin (PAE) cellulose nanofibers and silica NPs (as shown in Fig. 4). The NPs functioned as spacers which controls the pore size of the nanofibers. The used membranes were recycled for traditional paper production. Interestingly, Medina-Gonzalez et al. [71] substituted highly toxic NMP (conventional solvent) with methyl lactate (bio-solvent) for synthesis of CA. The synthesized

membrane exhibited a sponge-like matrix having a pore size similar to that of commercial UF membranes. Results indicated that the fabricated membranes could be used for water treatment upto a transmembrane pressure of 5 bar. In another study, NF cellulose membranes were fabricated via phase inversion using 1-ethyl-3-methylimidazolium acetate [72]. The synthesized membrane was stable in different solvents. These membranes also displayed dye rejection similar to the available organic solvent-based NF membranes with a maximum Brilliant Blu R rejection capacity of ~100 %.

Figure 4. Interconnected cellulose nanofibers and silica NPs (Adapted from Galiano et al. [47]).

5.2.2 Alginate

Alginate is a natural polysaccharide extracted from brown algae (*Phaeophyceae*) [73]. Alginates have been widely investigated and applied in food and biomedical sectors [47]. It is composed of straight chains of *L*-gluronic acid and 1-4 linked mannuronic acid [47]. Algal extracts obtained by treating algae with NaOH are filtered and precipitated using Na/Ca chloride to yield alginates [73]. Alginates are mainly blended with chitosan (CS), for the synthesis of multilayer membranes for water treatment. Layers of this membrane are held together by the electrostatic interactions occurring between poly-cations of the protonated amines of CS chains and the poly-anions of the carboxylate groups of alginates [47,74]. Alginate-CS membranes have been previously reported for herbicide

adsorption [74]. The synthesized membrane had numerous sites on their surface which was exposed to the positive/negative charged particles of the pesticide molecules to bind to. Authors also described the method for the preparation of bilayer membranes for the purpose of absorbing Paraquat from water and eventually, herbicides like Clomazone, Difenzoquat and Diquat from contaminated water [74,75]. The blended biopolymeric membranes simultaneously adsorbed negatively charged herbicides and positively charged compounds on the CS and alginate layer respectively. Paiva et al [76] synthesized uniform and homogenous alginate-CS layers alternate layers of the same in a Petri dish. Incorporation of metal in the membrane composition primarily depends upon solution pH and the metal's affinity for the polymer being used. These organic-inorganic membranes may be utilized as potential antimicrobial systems for inhibiting bacterial growth.

5.2.3 Starch

Starch is a plant-based polymer synthesized via photosynthesis. Starch consists of amylose (30 %), amylopectin (70 %) and other lipids and proteins (<1 %) from plants. Starch is a cost effective, completely biodegradable material having good renewability [47]. Starch based polymers have been widely applied as edible films and food packaging in the food industry. However, these materials have been rarely investigated as a component of polymeric membranes. A recent study had reported an antibacterial membrane synthesized using a blend of hydrolyzed starch and CA in presence of glycerol as a plasticizer via phase inversion [77]. The antibacterial activity of these membranes was tested with *E. coli*. Complete inhibition of bacterial growth on the membrane surface proved the applicability of these membranes in medical and food sectors. The presence of starch strongly contributed to the biodegradability of the membrane. Moreover, the total starch and polymer content was found to influence the hydrophilicity of the membrane. In another study, montmorillonite (MMT) and carboxymethyl cellulose (CMC) were blended as reinforcing fillers in a starch matrix for synthesis of biocomposite films [78]. Water resistance of starch was seen to improve by blending CMC with nano clay. Diffusion of water molecules through this composite was found to decrease with a simultaneous reduction of membrane hydrophilicity caused by the saturation of hydrogen bonds of the hydroxyl groups present in MMT layers and CMC starch chains.

5.3 Biopolymers derived from animal sources

5.3.1 Chitosan (CS)

Chitin, poly(β -(1-4)-N-acetyl-D-glucosamine) was identified for the first time in 1884 [47]. Chitin, a natural, biocompatible and nontoxic polysaccharide extracted from shells

of crustaceans, has attracted significant scientific interest in recent times. Nearly 50% deacetylation of chitin results in the formation of CS, a biorenewable material soluble in acidic aqueous solvents [79]. Raval et al. [80] reported the synthesis of a high flux thin-film composite (TFC) RO membrane modified with CS. The CS modified membrane reportedly exhibited higher water flux in comparison to unmodified TFC RO membranes. Moreover, an increase in water flux of the CS modified membranes was recorded with a parallel increase in temperature without any loss of their salt rejection efficiency. This process is more promising than solar powered RO, where low-grade thermal energy is utilized for heating the feed water. In another study, Egusa et al. [81] investigated the nano-fibrillation of CS. They synthesized nanofiber sheets from nanofibrillated CS under neutral conditions. The modified CS nanofiber sheets strongly inhibited mycelial growth of *Microsporum* and *Trichophyton* and were resistant to fungal degradation. In another study, Cooper et al. [82] synthesized CS-based membranes via electrospinning for application in antibacterial filters. Incorporation of CS (25 %) within the nanofibrous membrane resulted in 50 % inhibition of *S. aureus* colonization in comparison to unmodified membranes. In another study, authors have investigated the antibacterial activity of the CS membranes [47]. Results obtained in this study indicated that antibacterial activity of CS membranes were dependent upon the degree of deacetylation of CS [47]. The CS membrane reported in this study had potential bactericidal properties. Hence, CS may be considered as an efficient material for synthesis of membranes for water treatment.

5.3.2 Collagen and sericin

Collagen is the most abundant protein present in the bones, cartilages, skin and tendons [47]. Collagen consists of several polypeptides and is extensively used in the biomedical industry. Collagen may be extracted from different animal species. However, it is primarily derived from byproducts of slaughter. Sericin, the major component of silk, is a macromolecular protein made up of 17–18 different amino acids [83]. Collagen and sericin are usually extracted using enzymatic, chemical, and ultrasound processes [84]. Previous studies have reported the synthesis of cross-linked hydrophilic membranes using collagen fibers and fibrils obtained from bovines [47]. This membrane offered an advantage of yielding high flux even at low temperatures. However, due to the proteinaceous nature of the membrane, it is sensitive to microbial degradation, high temperature and extreme pH. The collagen membranes reported in this study exhibited good water selectivity and separation efficiency in comparison to hydrophilic membranes. Nevertheless, rapid degradation is a major disadvantage of this collagen-based membrane [47]. For overcoming this limitation, collagen is often cross-linked to other polymers for membrane synthesis.

6. Factors affecting membrane efficacy

Membrane efficiency (in terms of permeate quality and flux) is reportedly guided by the parameters discussed as follows [85].

6.1 Operating condition

The membrane efficiency is firmly related to process parameters like temperature, operating pressure and flow rate.

6.1.1 Temperature

With the increase in temperature, the permeate flux also increases as rise in temperature causes a decline of viscosity and level of concentration polarization of oily wastewater [86]. Moreover, increase of temperature also decreases the removal of chemical oxygen demand (COD) and the electrical conductivity of oily wastewater [87]. In another study, membrane permeability was found to decline at temperatures above 24 °C [30]. However, in the same study it was observed that the effect of temperature was non-significant when the flux permeate was maintained at 11-12 L m⁻² h⁻¹. However, in presence of fouling, flux decrease irrespective of any rise in temperature [88]. Change in temperature causes the alteration of diffusion coefficient and rate of adsorption and in turn influences the flux.

6.1.2 Operating pressure

Flux reportedly increases with a parallel increase in pressure. However, does not occur in case of concentration polarization phenomenon and membrane fouling [86]. In another study, it was reported that an increase in operation pressure had resulted in a corresponding increase in dye rejection and the transport rate of solvent [89].

6.1.3 Flow rate

The increase in flow rate results in a corresponding increase of mass transport and permeates flux as well as a reduction of possible concentration polarization [89].

6.2 Membrane characteristics

According to a previous study, ployacrylonitrile membranes with greater hydrophilicity can remove surfactants more efficiently than fluoropolymers with comparatively lower hydrophilicity though the latter exhibits higher resistance to temperature and chemicals [85]. Moreover, the membranes reported in this study yielded higher permeate flux when used for crossflow or vibratory-enhanced filtration than in a dead-end mode. In another study, tubular polyamide loose -NF membranes reportedly yielded a higher permeate flux

(75 L m⁻²) but lower removal of organics (98%) and conductivity (70%) in comparison to tubular tight-NF membranes that generated lower flux (49 L m⁻²) and less efficient removal of organics (99.7%) and conductivity (95%) [85]. However, almost no significant difference was noted in stable permeate fluxes of metal membranes differing in pore sizes (0.5, 1, and 5 μm) when used for direct filtration of greywater [85]. Moreover, permeate yielded by metal membranes having a pore size of 0.5 μm was of comparatively higher quality (in terms of color, COD, conductivity, and turbidity than those generated by metal membranes with pore sizes of 1 and 5 μm. Thus, from this result, it can be inferred that the selection of appropriate membrane is of significant importance for achieving maximum efficiency in case of wastewater treatment.

Membrane charge, hydrophilicity and pore size are closely associated with its performance efficiency [85]. The charge of membrane and solute must be considered as significant parameters for guiding separation processes. In scenarios where charge of the solutes differs from charge of the membrane, a larger gravitational force operates and increases the probability of membrane fouling. Membrane fouling eventually causes a decline in flux and alters membrane selectivity [85]. The membrane pore size is also a determining factor guiding rejection of uncharged contaminants. Moreover, hydrophilicity of a membrane is more implicative of higher interaction with water than lower interactions with solutes. Nevertheless, hydrophobic membranes have higher antifouling potential and lower flux in comparison to hydrophilic ones [86].

6.2.1 Feed characteristics

Charge, chemical nature, geometry, hydrophilicity and pH of feed solutions exert significant effects on membrane efficiency. pH of the feed solution can influence and even alter membrane charge. At a pH exceeding the isoelectric point, the membrane will acquire negative charge and vice versa [86]. The isoelectric point differs with membrane type [86]. The change in pH also influences membrane hydrophilicity [86]. Moreover, temperature of the feed solutions accelerates the process of mass transfer through the membrane [87].

6.2.2 Fouling

In wastewater, the major fouling components are particulate and dissolved matter (both inorganic and organic), salts (both multivalent and monovalent), pathogens and surfactant [86]. According to a previous study, hydraulic resistance of the fouling cake layers is guided by the amount of organic matter and calcium present in greywater and the formed cake may enhance micropollutant removal by adsorption of the same within its layers [86]. However, surfactants (like sodium dodecyl sulfate) strongly interact with calcium

present in effluents to form micelles that may accelerate membrane fouling. This often leads to unintended accumulation of organic substance in permeates as the surfactant outcompetes organics and occupies the active adsorption sites of calcium. Moreover, shower gels and conditioners present in greywater can reportedly cause more serious fouling of the membrane in comparison to shampoos and hand soaps [86].

6.3 Pretreatment of membrane

MF (0.2 μm) based pretreatment is more effective than cartridge (10 μm) based ones for enhancing the water flux and permeate quality of RO processes [90]. Another study reported that membrane filtration integrated with photocatalytic processes exhibit higher efficiency for degradation of organic pollutant present in greywater [85]. Moreover, presence of TiO_2 (photocatalyst) significantly reduced membrane fouling through the formation of large organo- TiO_2 aggregates. However, photocatalytic efficiency of TiO_2 may be affected adversely by these aggregates. Results obtained in this study indicated a reduction in membrane fouling with a corresponding increase in duration of UV irradiation [85].

7. Application of polymeric membranes for water purification

An extensive review of recent literature suggested that polymer nanocomposite based UF membranes (as evident from both Table 1 and Table 2) have been most widely investigated for desalination and wastewater treatment. Incorporation of NPs in polymer matrices was found to enhance membrane porosity and hydrophilicity as well as antifouling properties. Composite UF membranes have been most widely investigated and applied for desalination and wastewater treatment. These membranes have been provided high flux and solutes retention of good quality. Incorporation of photocatalytic NPs into polymeric membranes has further facilitated efficient degradation of pollutants in solution besides rejection. However, membrane efficiency and reusability should be determined using real effluents for elucidating the feasibility of using these membranes on an industrial scale.

Table 1. Polymer nanocomposite membranes for desalination

Polymer type	Membrane	Major findings	Ref.
2-hydroxyethyl methacrylate, glycidyl methacrylate and glycerol methacrylate were crosslinked with poly (ethylene glycol) dimethacrylate	NF	<ul style="list-style-type: none"> • Chemical modification of a series of water content equivalent copolymers increased water/salt permeability selectivity; • Distributed hydrophilic functional groups may lead to increased selectivity and may represent a strategy for improving water/salt selectivity of advanced membrane materials 	[91]
Cellulose acetate / poly-ethylene glycol with integrated candle soot NPs	RO	<ul style="list-style-type: none"> • CS NPs contributed in improving the salt rejection % with a slight reduction in the water flux behavior; • 93% salt rejection using the membranes; 	[92]
TiO ₂ -sulfonated polymer embedded polyetherimide	UF	<ul style="list-style-type: none"> • Three different electrolytes (NaCl, Na₂SO₄ and MgSO₄) with varying concentrations from 50 - 500 mg L⁻¹ and groundwater were filtered; • Fabricated membranes are lower MWCO UF membranes (8kDa); • Higher flux was recorded for groundwater filtration. 	[93]
Negatively charged polyaniline (PANI) nanoparticles incorporated within polysulfone (PSF)	UF	<ul style="list-style-type: none"> • 2 wt% PANI loading leads to a 25 fold increase in the molecular weight cut-off (from 0.2 to 4.8 kDa); • Improvement in porosity (from 20% to 64%), and a 2-fold increase in permeability (from 8×10^{-12} to 16×10^{-12} m³ m⁻² Pa⁻¹ s⁻¹); • 2.5 times enhancement in the permeate flux; • Salt rejection between 40–53%, equivalent to the NF performance. 	[94]
PVDF hollow fiber membrane	UF	<ul style="list-style-type: none"> • Treatment of shale gas fracturing wastewater; • Significantly reduced fouling of UF membranes 	[95]

Hydrolyzed polyacrylonitrile (PAN) modified with PEI	NF	<ul style="list-style-type: none"> • Treatment of textile effluent; • Membrane prepared at optimized condition achieved a high flux and dye rejection (~97%) and lowest irreversible fouling ratio (8.1%) for humic acid 	[96]
Polyethersulfone	UF	<ul style="list-style-type: none"> • Lower MWCO membranes exhibited a negligible relative flux decline; • 90% retention of humic acid; • Good antifouling property 	[97]
Monolayer graphene (G) coated polypropylene (PP) and PVDF	MF	<ul style="list-style-type: none"> • G – PP membranes exhibited better desalination efficiency than G – PVDF ones; • Both membranes had defects that improved with Nylon 6,6 sealing; • Optimum sealing resulted in 84% blockage of KCl ions 	[98]
Cellulose/graphene oxide composite	MF	<ul style="list-style-type: none"> • High water flux ($334.7 \pm 10.4 \text{ L m}^{-2} \text{ h}^{-1}$); • Good antifouling property; • Suitable for pretreatment of seawater prior to RO 	[99]
Polyamide – graphene oxide composite	RO-MF	<ul style="list-style-type: none"> • High salt rejection (99.7%); • High permeance ($3.0 \text{ L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$); • Membranes exhibited good stability and anti-fouling property 	[100]

Table 2. Polymer nanocomposite membranes for wastewater treatment

Polymer type	Membrane	Major findings	Ref.
1-Methyl-2-pyrrolidinone, polyvinylpyrrolidone and polysulfone with graphene oxide and carboxylic-functionalized carbon nanotube fillers	UF	<ul style="list-style-type: none"> • Rejection of methyl orange ($17.8 \pm 6.7\%$) is observed to be always higher than that of methylene blue ($1.9 \pm 1.5\%$); • > 90% rejection of bovine serum albumin (BSA); • Addition of carbon nanofillers enhanced the rejection of negatively charged molecules with increased permeability at low nanofiller mass loading 	[101]

Mesoporous carbon (MPC) bearing Ag NP loaded polyethersulfone	UF	<ul style="list-style-type: none"> • Bacterial attachment on the membrane surface was reduced dramatically; • Damage of <i>Bacillus subtilis</i> (92.94%) and <i>Escherichia coli</i> (93.21%); <p>The polymeric mixed matrix membrane entirely mitigated biofouling over 99% by the combination of the bactericidal effect of silver and the anti-adhesion properties of MPC.</p>	[102]
Poly(m-phenylene isophthalamide)	UF	<ul style="list-style-type: none"> • Membrane exhibited a high porosity, narrow pore radius distribution and excellent hydrophilicity, leading to its high performance in the filtration process; • Exhibit good antifouling properties; • Efficient separation of BSA and phosphates. 	[103]
Polydopamine NP coated polyethersulfone	UF	<ul style="list-style-type: none"> • Membrane exhibited 92.9 % BSA rejection and $166 \text{ L m}^{-2} \text{ h}^{-1}$ pure water flux; • Membrane also demonstrated static adsorption capacities of 20.23, 17.01 and 10.42 mg g^{-1} of Pb^{2+}, Cd^{2+} and Cu^{2+} respectively; • Adsorption data could be fitted better with the Langmuir isotherm model and pseudo 2nd order kinetics 	[104]
Alumina (Al_2O_3) NP embedded in PES membranes	UF	<ul style="list-style-type: none"> • Thinner skin layer, higher porosity and hydrophilicity enhanced water permeation almost by three times; • Composite formation enhanced uptake of Cu from aqueous solutions 	[105]
Cellulose acetate composite with organically modified montmorillonite	UF	<ul style="list-style-type: none"> • Enhanced membrane hydrophilicity; • Enhanced adsorption of Humic acid 	[106]

Electrospun PES nanofibers	MF	<ul style="list-style-type: none"> • Enhanced flux and anti-fouling properties; • Improved water flux; • High retention of TiO₂ microparticles (99%) 	[107]
PVDF nanofibers	MF	<ul style="list-style-type: none"> • Improved membrane hydrophilicity; • High flux rates under low pressure; • High retention of polystyrene microparticles (99%) 	[108]
TiO ₂ NP coated PES and PVDF	MF	<ul style="list-style-type: none"> • Enhanced flux and anti-fouling properties; • Membranes exhibited high photocatalytic degradation of methylene blue and anti-inflammatory drugs (ibuprofen and diclofenac); • Membranes exhibited good reuse potential without any loss of photocatalytic activity 	[109]
Carboxylated MWCNT/ PES nanocomposite	MF	<ul style="list-style-type: none"> • Increased membrane porosity and hydrophilicity; • High pure water permeance (20 Lm⁻²h⁻¹bar⁻¹); • Enhanced removal of bromothymol blue and methyl orange (95%) 	[110]

Conclusion

Polymer membrane-based desalination and wastewater treatment processes have significantly improved over the last few years. However, certain initiatives can promote these processes further. Only a fraction of these membranes has been synthesized using “green” materials or processes. Further studies are required for reducing the thickness of membrane layers and defects present in the membrane. Investigations should also include life cycle assessment methodologies for ensuring complete green synthesis of membranes. More utilization of biopolymers is encourage able for synthesis of nanocomposites for preparing membranes. These membranes should be tested for performance efficiency using real effluents for assessment of their true potential for desalination and water treatment.

References

- [1] Coping with water scarcity. A strategic issue and priority for system-wide action. UN-water (2006).
- [2] R. Das, M.E. Ali, S.B.A. Hamid, S. Ramakrishna, Z.Z. Chowdhury, Carbon nanotube membranes for water purification: a bright future in water desalination, *Desalination* 336 (2014) 97–109. <https://doi.org/10.1016/j.desal.2013.12.026>
- [3] P. Banerjee, R. Das, P. Das, A. Mukhopadhyay, Membrane Technology, in: R. Das (Ed.), *Carbon Nanotubes for Clean Water*, Springer, Cham, 2018, pp. 127-150. https://doi.org/10.1007/978-3-319-95603-9_6
- [4] P.S. Goh, A.F. Ismail, B.C. Ng, Carbon nanotubes for desalination: performance evaluation and current hurdles, *Desalination* 308 (2013) 2–14. <https://doi.org/10.1016/j.desal.2012.07.040>
- [5] Z. Zia, A. Hartland, M.R. Mucalo, Use of low-cost biopolymers and biopolymeric composite systems for heavy metal removal from water, *Int. J. Env. Sci. Technol.* 17 (2020) 4389–4406. <https://doi.org/10.1007/s13762-020-02764-3>
- [6] R. Das, *Polymeric Materials for Clean Water*, Springer, Berlin, Germany, 2019. <https://doi.org/10.1007/978-3-030-00743-0>
- [7] L.Y. Ng, A.W. Mohammad, C.P. Leo, N. Hilal, Polymeric membranes incorporated with metal/metal oxide nanoparticles: a comprehensive review, *Desalination* 308 (2013) 15–33. <https://doi.org/10.1016/j.desal.2010.11.033>
- [8] N.L. Le, S.P. Nunes, Materials and membrane technologies for water and energy sustainability, *Sustain. Mater. Technol.* 7 (2016) 1–28. <https://doi.org/10.1016/j.susmat.2016.02.001>
- [9] A. Abdel-Karim, T.A. Gad-Allah, A.S. El-Kalliny, S.I.A. Ahmed, E.R. Souaya, M.I. Badawy, M. Ulbricht, Fabrication of modified polyethersulfone membranes for wastewater treatment by submerged membrane bioreactor, *Sep. Purif. Technol.* 175 (2017) 36–46. <https://doi.org/10.1016/j.seppur.2016.10.060>
- [10] B.B. Ashoor, S. Mansour, A. Giwa, V. Dufour, S.W. Hasan, Principles and applications of direct contact membrane distillation (DCMD): a comprehensive review, *Desalination* 398 (2016) 222–246. <https://doi.org/10.1016/j.desal.2016.07.043>
- [11] A. Giwa, S. Daer, I. Ahmed, P. Marpu, S. Hasan, Experimental investigation and artificial neural networks ANNs modeling of electrically-enhanced membrane bioreactor for wastewater treatment, *J. Water Proc. Eng.* 11 (2016) 88–97. <https://doi.org/10.1016/j.jwpe.2016.03.011>
- [12] A. Giwa, S. Hasan, Theoretical investigation of the influence of operating conditions on the treatment performance of an electrically-induced membrane

- bioreactor, *J. Water Proc. Eng.* 6 (2015) 72–82.
<https://doi.org/10.1016/j.jwpe.2015.03.004>
- [13] X. Wang, C. Wang, C.Y. Tang, T. Hu, X. Li, Y. Ren, Development of a novel anaerobic membrane bioreactor simultaneously integrating microfiltration and forward osmosis membranes for low-strength wastewater treatment, *J. Mem. Sci.* 527 (2017) 1–7. <https://doi.org/10.1016/j.memsci.2016.12.062>
- [14] B.B. Ashoor, H. Fath, W. Marquardt, A. Mhamdi, Dynamic modeling of direct contact membrane distillation processes, in: I.A. Karimi, R. Srinivasan (Eds.), *Computer Aided Chemical Engineering*, Elsevier, Netherlands, 2012, pp. 170–174.
<https://doi.org/10.1016/B978-0-444-59507-2.50026-3>
- [15] S.W. Hasan, M. Elektorowicz, J.A. Oleszkiewicz, Start-up period investigation of pilot-scale submerged membrane electro-bioreactor (SMEBR) treating raw municipal wastewater, *Chemosphere* 97 (2014) 71–77.
<https://doi.org/10.1016/j.chemosphere.2013.11.009>
- [16] C.H. Neoh, Z.Z. Noor, N.S.A. Mutamim, C.K. Lim, Green technology in wastewater treatment technologies: integration of membrane bioreactor with various wastewater treatment systems, *Chem. Eng. J.* 283 (2016) 582–594.
<https://doi.org/10.1016/j.cej.2015.07.060>
- [17] J. Lee, H.R. Chae, Y.J. Won, K. Lee, C.H. Lee, H.H. Lee, I.C. Kim, J.M. Lee, Graphene oxide nanoplatelets composite membrane with hydrophilic and antifouling properties for wastewater treatment, *J. Mem. Sci.* 448 (2013) 223–230.
<https://doi.org/10.1016/j.memsci.2013.08.017>
- [18] M. Aslam, A. Charfi, G. Lesage, M. Heran, J. Kim, Membrane bioreactors for wastewater treatment: a review of mechanical cleaning by scouring agents to control membrane fouling, *Chem. Eng. J.* 307 (2017) 897–913.
<https://doi.org/10.1016/j.cej.2016.08.144>
- [19] P. Krzeminski, L. Leverette, S. Malamis, E. Katsou, Membrane bioreactors—a review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects, *J. Mem. Sci.* 527 (2017) 207–227.
<https://doi.org/10.1016/j.memsci.2016.12.010>
- [20] W. Luo, H.V. Phan, M. Xie, F.I. Hai, W.E. Price, M. Elimelech, L.D. Nghiem, Osmotic versus conventional membrane bioreactors integrated with reverse osmosis for water reuse: biological stability, membrane fouling, and contaminant removal, *Water Res.* 109 (2017) 122–134. <https://doi.org/10.1016/j.watres.2016.11.036>
- [21] X. Wang, V.W.C. Chang, C.Y. Tang, Osmotic membrane bioreactor (OMBR) technology for wastewater treatment and reclamation: advances, challenges, and

- prospects for the future, *J. Mem. Sci.* 504 (2016) 113-132.
<https://doi.org/10.1016/j.memsci.2016.01.010>
- [22] G. Qiu, Y.P. Ting, Short-term fouling propensity and flux behavior in an osmotic membrane bioreactor for wastewater treatment, *Desalination* 332 (2014) 91–99.
<https://doi.org/10.1016/j.desal.2013.11.010>
- [23] B. Díez, N. Roldán, A. Martín, A. Sotto, J.A. Perdigón-Melón, J. Arsuaga, R. Rosal, Fouling and biofouling resistance of metal-doped mesostructured silica/polyethersulfone ultrafiltration membranes, *J. Mem. Sci.* 526 (2017) 252–263.
<https://doi.org/10.1016/j.memsci.2016.12.051>
- [24] S. Mokhtari, A. Rahimpour, A.A. Shamsabadi, S. Habibzadeh, M. Soroush, Enhancing performance and surface antifouling properties of polysulfone ultrafiltration membranes with salicylate-alumoxane nanoparticles, *Appl. Surf. Sci.* 393 (2017) 93–102. <https://doi.org/10.1016/j.apsusc.2016.10.005>
- [25] Y. Orooji, M. Faghih, A. Razmjou, J. Hou, P. Moazzam, N. Emami, M. Aghababaei, F. Nourisfa, V. Chen, W. Jin, Nanostructured mesoporous carbon polyethersulfone composite ultrafiltration membrane with significantly low protein adsorption and bacterial adhesion, *Carbon* 111 (2017) 689–704.
<https://doi.org/10.1016/j.carbon.2016.10.055>
- [26] N. Sharma, M.K. Purkait, Impact of synthesized amino alcohol plasticizer on the morphology and hydrophilicity of polysulfone ultrafiltration membrane, *J. Mem. Sci.* 522 (2017) 202–215. <https://doi.org/10.1016/j.memsci.2016.08.068>
- [27] M. Son, H. Kim, J. Jung, S. Jo, H. Choi, Influence of extreme concentrations of hydrophilic pore-former on reinforced polyethersulfone ultrafiltration membranes for reduction of humic acid fouling, *Chemosphere* 179 (2017) 194–201.
<https://doi.org/10.1016/j.chemosphere.2017.03.101>
- [28] S. Velu, G. Arthanareeswaran, H. Lade, Removal of organic and inorganic substances from industry wastewaters using modified aluminosilicate-based polyethersulfone ultrafiltration membranes, *Environ. Prog. Sustain. Energy* 36 (2017) 1612-1620. <https://doi.org/10.1002/ep.12614>
- [29] H. Wu, Y. Liu, L. Mao, C. Jiang, J. Ang, X. Lu, Doping polysulfone ultrafiltration membrane with TiO₂-PDA nanohybrid for simultaneous self-cleaning and self-protection, *J. Mem. Sci.* 532 (2017) 20–29.
<https://doi.org/10.1016/j.memsci.2017.03.010>
- [30] A. Behboudi, Y. Jafarzadeh, R. Yegani, Polyvinyl chloride/polycarbonate blend ultrafiltration membranes for water treatment, *J. Mem. Sci.* 534 (2017) 18–24.
<https://doi.org/10.1016/j.memsci.2017.04.011>

- [31] Y.W. Huang, Z.M. Wang, X. Yan, J. Chen, Y.J. Guo, W.Z. Lang, Versatile polyvinylidene fluoride hybrid ultrafiltration membranes with superior antifouling, antibacterial and self-cleaning properties for water treatment, *J Colloid Interf. Sci.* 505 (2017) 38–48. <https://doi.org/10.1016/j.jcis.2017.05.076>
- [32] Z. Maghsoud, M. Pakbaz, M.H.N. Famili, S.S. Madaeni, New polyvinyl chloride/thermoplastic polyurethane membranes with potential application in nanofiltration, *J. Mem. Sci.* 541 (2017) 271–280. <https://doi.org/10.1016/j.memsci.2017.07.001>
- [33] H. Wang, Z.-M. Wang, X. Yan, J. Chen, W.-Z. Lang, Y.-J. Guo, Novel organic-inorganic hybrid polyvinylidene fluoride ultrafiltration membranes with antifouling and antibacterial properties by embedding N-halamine functionalized silica nanospheres, *J. Ind. Eng. Chem.* 52 (2017) 295–304. <https://doi.org/10.1016/j.jiec.2017.03.059>
- [34] B. Yang, X. Yang, B. Liu, Z. Chen, C. Chen, S. Liang, L.-Y. Chu, J. Crittenden, PVDF blended PVDF-g-PMAA pH-responsive membrane: effect of additives and solvents on membrane properties and performance, *J. Mem. Sci.* 541 (2017) 558–566. <https://doi.org/10.1016/j.memsci.2017.07.045>
- [35] C. Zhao, J. Lv, X. Xu, G. Zhang, Y. Yang, F. Yang, Highly antifouling and antibacterial performance of poly (vinylidene fluoride) ultrafiltration membranes blending with copper oxide and graphene oxide nanofillers for effective wastewater treatment, *J. Colloid Interf. Sci.* 505 (2017) 341–351. <https://doi.org/10.1016/j.jcis.2017.05.074>
- [36] S. Daer, J. Kharraz, A. Giwa, S.W. Hasan, Recent applications of nanomaterials in water desalination: a critical review and future opportunities, *Desalination* 367 (2015) 37–48. <https://doi.org/10.1016/j.desal.2015.03.030>
- [37] A. Giwa, N. Akther, A. Al Housani, S. Haris, S.W. Hasan, Recent advances in humidification dehumidification (HDH) desalination processes: improved designs and productivity, *Renew. Sustain. Energy Rev.* 57 (2016) 929–944. <https://doi.org/10.1016/j.rser.2015.12.108>
- [38] D. Qadir, H. Mukhtar, L.K. Keong, Mixed matrix membranes for water purification applications, *Sep. Purif. Rev.* 46 (2017) 62–80. <https://doi.org/10.1080/15422119.2016.1196460>
- [39] H. Rabiee, V. Vatanpour, M.H.D.A. Farahani, H. Zarrabi, Improvement in flux and antifouling properties of PVC ultrafiltration membranes by incorporation of zinc oxide (ZnO) nanoparticles, *Sep. Purif. Technol.* 156 (2015) 299–310. <https://doi.org/10.1016/j.seppur.2015.10.015>

- [40] A. Martín, J.M. Arsuaga, N. Roldán, J. de Abajo, A. Martínez, A. Sotto, Enhanced ultrafiltration PES membranes doped with mesostructured functionalized silica particles, *Desalination* 357 (2015) 16–25. <https://doi.org/10.1016/j.desal.2014.10.046>
- [41] K.L. Mercer, 2017 State of the water industry: strengthening our connections, *J. American Water Works Assoc.* 109 (2017) 56–65. <https://doi.org/10.5942/jawwa.2017.109.0090>
- [42] J.A. Prince, S. Bhuvana, K.V.K. Boodhoo, V. Anbharasi, G. Singh, Synthesis and characterization of PEG-Ag immobilized PES hollow fiber ultrafiltration membranes with long lasting antifouling properties, *J. Mem. Sci.* 454 (2014) 538–548. <https://doi.org/10.1016/j.memsci.2013.12.050>
- [43] H. Yu, Y. Zhang, X. Sun, J. Liu, H. Zhang, Improving the antifouling property of polyethersulfone ultrafiltration membrane by incorporation of dextran grafted halloysite nanotubes, *Chem. Eng. J.* 237 (2014) 322–328. <https://doi.org/10.1016/j.cej.2013.09.094>
- [44] L. Shao, Z.X. Wang, Y.L. Zhang, Z.X. Jiang, Y.Y. Liu, A facile strategy to enhance PVDF ultrafiltration membrane performance via self-polymerized polydopamine followed by hydrolysis of ammonium fluotitanate, *J. Mem. Sci.* 461 (2014) 10–21. <https://doi.org/10.1016/j.memsci.2014.03.006>
- [45] P. Kanagaraj, A. Nagendran, D. Rana, T. Matsuura, S. Neelakandan, T. Karthikkumar, A. Muthumeenal, Influence of N-phthaloyl chitosan on poly (ether imide) ultrafiltration membranes and its application in biomolecules and toxic heavy metal ion separation and their antifouling properties, *Appl. Surf. Sci.* 329 (2015) 165–173. <https://doi.org/10.1016/j.apsusc.2014.12.082>
- [46] C. Liu, H. Mao, J. Zheng, S. Zhang, Tight ultrafiltration membrane: preparation and characterization of thermally resistant carboxylated cardo poly (arylene ether ketone)s (PAEK-COOH) tight ultrafiltration membrane for dye removal, *J. Mem. Sci.* 530 (2017) 1–10. <https://doi.org/10.1016/j.memsci.2017.02.005>
- [47] F. Galiano, K. Briceno, T. Marino, A. Molino, K.V. Christensen, A. Figoli, Advances in biopolymer-based membrane preparation and applications, *J. Mem. Sci.* 564 (2018) 562–586. <https://doi.org/10.1016/j.memsci.2018.07.059>
- [48] Y. Gu, J. François, Bio-based solvents: an emerging generation of fluids for the design of eco-efficient processes in catalysis and organic chemistry, *Chem. Soc. Rev.* 42 (2013) 9550–9570. <https://doi.org/10.1039/c3cs60241a>
- [49] M. Niaounakis, *Biopolymers: applications and trends*, first ed., William Andrew, New York, 2015.

- [50] T. Tanaka, M. Ueno, Y. Watanabe, T. Kouya, M. Taniguchi, D.R. Lloyd, Poly(l-lactic acid) microfiltration membrane formation via thermally induced phase separation with drying, *J. Chem. Eng. Japan* 44 (2011) 467–475.
<https://doi.org/10.1252/jcej.11we030>
- [51] S. Chitrattha, T. Phaechamud, Modifying poly(L-lactic acid) matrix film properties with high loaded poly(ethylene glycol), *Key Eng. Mater.* 545 (2013) 57–62.
<https://doi.org/10.4028/www.scientific.net/KEM.545.57>
- [52] T. Phaechamud, S. Chitrattha, Pore formation mechanism of porous poly(dl-lactic acid) matrix membrane, *Mater. Sci. Eng. C* 61 (2016) 744–752.
<https://doi.org/10.1016/j.msec.2016.01.014>
- [53] A. Moriya, P. Shen, Y. Ohmukai, T. Maruyama, H. Matsuyama, Reduction of fouling on poly(lactic acid) hollow fiber membranes by blending with poly(lactic acid)-polyethylene glycol-poly(lactic acid) triblock copolymers, *J. Mem. Sci.* 415–416 (2012) 712–717. <https://doi.org/10.1016/j.memsci.2012.05.059>
- [54] H. Minbu, A. Ochiai, T. Kawase, M. Taniguchi, D.R. Lloyd, T. Tanaka, Preparation of poly(L-lactic acid) microfiltration membranes by a nonsolvent-induced phase separation method with the aid of surfactants, *J. Mem. Sci.* 479 (2015) 85–94.
<https://doi.org/10.1016/j.memsci.2015.01.021>
- [55] A.C. Chinyerenwa, W. Han, Q. Zhang, Y. Zhuang, K.H. Munna, C. Ying, H. Yang, W. Xu, Structure and thermal properties of porous polylactic acid membranes prepared via phase inversion induced by hot water droplets, *Polymer* 141 (2018): 62–69. <https://doi.org/10.1016/j.polymer.2018.03.011>
- [56] M.M. Reddy, S. Vivekanandhan, M. Misra, S.K. Bhatia, A.K. Mohanty, Biobased plastics and bionanocomposites: current status and future opportunities, *Prog. Polym. Sci.* 38 (2013) 1653–1689. <https://doi.org/10.1016/j.progpolymsci.2013.05.006>
- [57] H.C. Chang, T. Sun, N. Sultana, M.M. Lim, T.H. Khan, A.F. Ismail, Conductive PEDOT:PSS coated polylactide (PLA) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) electrospun membranes: Fabrication and characterization, *Mater. Sci. Eng. C* 61 (2016) 396–410. <https://doi.org/10.1016/j.msec.2015.12.074>
- [58] K. Keawsupsak, A. Jaiyu, J. Pannoi, P. Somwongsa, N. Wanthausk, P. Sueprasita, C. Eamchotchawalit, Poly(lactic acid)/biodegradable polymer blend for the preparation of flat-sheet membrane, *J. Teknol. Sci. Eng.* 69 (2014) 99–102.
<https://doi.org/10.11113/jt.v69.3405>
- [59] M. Villegas, E.F. Castro Vidaurre, J.C. Gottifredi, Sorption and pervaporation of methanol/water mixtures with poly(3-hydroxybutyrate) membranes, *Chem. Eng. Res. Des.* 94 (2015) 254–265. <https://doi.org/10.1016/j.cherd.2014.07.030>

- [60] M. Villegas, A.I. Romero, M.L. Parentis, E.F. Castro Vidaurre, J.C. Gottifredi, Acrylic acid plasma polymerized poly(3-hydroxybutyrate) membranes for methanol/MTBE separation by pervaporation, *Chem. Eng. Res. Des.* 109 (2016) 234–248. <https://doi.org/10.1016/j.cherd.2016.01.018>
- [61] V. Ghaffarian, S.M. Mousavi, M. Bahreini, H. Jalaei, Polyethersulfone/poly (butylene succinate) membrane: effect of preparation conditions on properties and performance, *J. Ind. Eng. Chem.* 20 (2014) 1359–1366. <https://doi.org/10.1016/j.jiec.2013.07.019>
- [62] V. Ghaffarian, S.M. Mousavi, M. Bahreini, Effect of blend ratio and coagulation bath temperature on the morphology, tensile strength and performance of cellulose acetate/poly(butylene succinate) membranes, *Desalin. Water Treat.* 54 (2015) 473–480. <https://doi.org/10.1080/19443994.2014.883329>
- [63] V. Ghaffarian, S.M. Mousavi, M. Bahreini, M. Afifi, Preparation and characterization of biodegradable blend membranes of PBS/CA, *J. Poly. Environ.* 21 (2013) 1150–1157. <https://doi.org/10.1007/s10924-012-0551-1>
- [64] M.A. El-Sheikh, S.M. El-Rafie, E.S. Abdel-Halim, M.H. El-Rafie, Green synthesis of hydroxyethyl cellulose-stabilized silver nanoparticles, *J. Polym.* 2013 (2013) 1–11. <https://doi.org/10.1155/2013/650837>
- [65] A.K. Mishra, *Smart Materials for Waste Water Applications*, Scrivener Publishing, Wiley, 2016. <https://doi.org/10.1002/9781119041214>
- [66] M.I. Baoxia, M. Elimelech, Gypsum scaling and cleaning in forward osmosis: measurements and mechanisms, *Environ. Sci. Technol.* 44 (2010) 2022–2028. <https://doi.org/10.1021/es903623r>
- [67] L.A. Goetz, B. Jalvo, R. Rosal, A.P. Mathew, Superhydrophilic anti-fouling electrospun cellulose acetate membranes coated with chitin nanocrystals for water filtration, *J. Membr. Sci.* 510 (2016) 238–248. <https://doi.org/10.1016/j.memsci.2016.02.069>
- [68] N. Naseri, A.P. Mathew, L. Girandon, M. Fröhlich, K. Oksman, Porous electrospun nanocomposite mats based on chitosan–cellulose nanocrystals for wound dressing: effect of surface characteristics of nanocrystals, *Cellulose* 22 (2015) 521–534. <https://doi.org/10.1007/s10570-014-0493-y>
- [69] P. Kanagaraj, A. Nagendran, D. Rana, T. Matsuura, Separation of macromolecular proteins and removal of humic acid by cellulose acetate modified UF membranes, *Int. J. Biol. Macromol.* 89 (2016) 81–88. <https://doi.org/10.1016/j.ijbiomac.2016.04.054>

- [70] S. Varanasi, Z.X. Low, W. Batchelor, Cellulose nanofibre composite membranes – biodegradable and recyclable UF membranes, *Chem. Eng. J.* 265 (2015) 138–146. <https://doi.org/10.1016/j.cej.2014.11.085>
- [71] Y. Medina-Gonzalez, P. Aimar, J.F. Lahitte, J.C. Remigy, Towards green membranes: preparation of cellulose acetate ultrafiltration membranes using methyl lactate as a biosolvent, *Int. J. Sustain. Eng.* 4 (2011) 75–83. <https://doi.org/10.1080/19397038.2010.497230>
- [72] F.M. Sukma, P.Z. Çulfaz-Emecen, Cellulose membranes for organic solvent nano filtration, *J. Membr. Sci.* 545 (2018) 329–336. <https://doi.org/10.1016/j.memsci.2017.09.080>
- [73] K.Y. Lee, D.J. Mooney, Alginate: properties and biomedical applications, *Prog. Polym. Sci.* 37 (2012) 106–126. <https://doi.org/10.1016/j.progpolymsci.2011.06.003>
- [74] M. Agostini de Moraes, D.S. Cocenza, F. da Cruz Vasconcellos, L.F. Fraceto, M.M. Beppu, Chitosan and alginate biopolymer membranes for remediation of contaminated water with herbicides, *J. Environ. Manag.* 131 (2013) 222–227. <https://doi.org/10.1016/j.jenvman.2013.09.028>
- [75] D.S. Cocenza, M.A. De Moraes, M.M. Beppu, L.F. Fraceto, Use of biopolymeric membranes for adsorption of paraquat herbicide from water, *Water Air. Soil Pollut.* 223 (2012) 3093–3104. <https://doi.org/10.1007/s11270-012-1092-x>
- [76] R.G. de Paiva, M.A. de Moraes, F.C. de Godoi, M.M. Beppu, Multilayer biopolymer membranes containing copper for antibacterial applications, *J. Appl. Polym. Sci.* 126 (2012): E17-E24. <https://doi.org/10.1002/app.36666>
- [77] A. Zarei, V. Ghaffarian, Preparation and characterization of biodegradable cellulose acetate-starch membrane, *Polym. Plast. Technol. Eng.* 52 (2013) 387–392. <https://doi.org/10.1080/03602559.2012.752831>
- [78] H. Almasi, B. Ghanbarzadeh, A.A. Entezami, Physicochemical properties of starch-CMC-nanoclay biodegradable films, *Int. J. Biol. Macromol.* 46 (2010) 1–5. <https://doi.org/10.1016/j.ijbiomac.2009.10.001>
- [79] P. Wu, M. Imai, Novel biopolymer composite membrane involved with selective mass transfer and excellent water permeability, in: R.Y. Ning (Ed.), *Advancing Desalination*, InTech, Rijeka, Croatia, 2012, pp. 57–81. <https://doi.org/10.5772/50697>
- [80] H.D. Raval, P.S. Rana, S. Maiti, A novel high-flux, thin-film composite reverse osmosis membrane modified by chitosan for advanced water treatment, *RSC Adv.* 5 (2015) 6687–6694. <https://doi.org/10.1039/C4RA12610F>

- [81] M. Egusa, R. Iwamoto, H. Izawa, M. Morimoto, H. Saimoto, H. Kaminaka, S. Ifuku, Characterization of chitosan nanofiber sheets for antifungal application, *Int. J. Mol. Sci.* 16 (2015) 26202–26210. <https://doi.org/10.3390/ijms161125947>
- [82] A. Cooper, R. Oldinski, H. Ma, J.D. Bryers, M. Zhang, Chitosan-based nanofibrous membranes for antibacterial filter applications, *Carbohydr. Polym.* 92 (2013) 254–259. <https://doi.org/10.1016/j.carbpol.2012.08.114>
- [83] Z. Wang, Y. Zhang, J. Zhang, L. Huang, J. Liu, Y. Li, G. Zhang, S.C. Kundu, L. Wang, Exploring natural silk protein sericin for regenerative medicine: an injectable, photoluminescent, cell-adhesive 3D hydrogel, *Scientific Reports* 4 (2014) 7064. <https://doi.org/10.1038/srep07064>
- [84] M.M. Schmidt, R.C.P. Dornelles, R.O. Mello, E.H. Kubota, M.A. Mazutti, A.P. Kempka, I.M. Demiate, Collagen extraction process, *Int. Food Res. J.* 23 (2016) 913–922.
- [85] B. Wu, Membrane-based technology in greywater reclamation: A review, *Sci. Total Environ.* 656 (2019) 184–200. <https://doi.org/10.1016/j.scitotenv.2018.11.347>
- [86] R. Mulyanti, H. Susanto, Wastewater treatment by nanofiltration membranes, *IOP Conf. Series: Earth Environ. Sci.* 142 (2018) 012017. <https://doi.org/10.1088/1755-1315/142/1/012017>
- [87] A. Rahimpour, B. Rajaeian, A. Hosienzadeh, S.S. Madaeni, F. Ghoreishi, Treatment of oily wastewater produced by washing of gasoline reserving tanks using self-made and commercial nanofiltration membranes, *Desalination* 265 (2011) 190–198. <https://doi.org/10.1016/j.desal.2010.07.051>
- [88] Z. Gönder, S.A. Beril, B. Hulusi, Advanced treatment of pulp and paper mill wastewater by nanofiltration process: Effects of operating conditions on membrane fouling, *Sep. Purif. Technol.* 76 (2011) 292–302. <https://doi.org/10.1016/j.seppur.2010.10.018>
- [89] A.M.F. Shaaban, A.I. Hafez, M.A. Abdel-Fatah, N.M. Abdel-Monem, M.H. Mahmoud, Process engineering optimization of nanofiltration unit for the treatment of textile plant effluent in view of solution diffusion model, *Egyptian J. Pet.* 25 (2016) 79–90. <https://doi.org/10.1016/j.ejpe.2015.03.018>
- [90] V.M. Boddu, T. Paul, M.A. Page, C. Byl, L. Ward, J. Ruan, Gray water recycle: Effect of pretreatment technologies on low pressure reverse osmosis treatment, *J. Environ. Chem. Eng.* 4 (2016) 4435–4443. <https://doi.org/10.1016/j.jece.2016.09.031>
- [91] H. Luo, K. Chang, K. Bahati, G.M. Geise, Engineering selective desalination membranes via molecular control of polymer functional groups, *Environ. Sci. Technol. Lett.* 6 (2019) 462–466. <https://doi.org/10.1021/acs.estlett.9b00351>

- [92] A.E. Abdelhamid, A.M. Khalil, Polymeric membranes based on cellulose acetate loaded with candle soot nanoparticles for water desalination, *J. Macromol. Sci. A* 56 (2019) 153-161. <https://doi.org/10.1080/10601325.2018.1559698>
- [93] Y. L. Thuyavan, N. Anantharaman, G. Arthanareeswaran, A.F. Ismail, R. V. Mangalaraja, Preparation and characterization of TiO₂-sulfonated polymer embedded polyetherimide membranes for effective desalination application, *Desalination* 365 (2015) 355-364. <https://doi.org/10.1016/j.desal.2015.03.004>
- [94] R. Mukherjee, R. Sharma, P. Saini, S. De., Nanostructured polyaniline incorporated ultrafiltration membrane for desalination of brackish water, *Environ. Sci. Water Res. Technol.* 1 (2015) 893-904. <https://doi.org/10.1039/C5EW00163C>
- [95] H. Chang, T. Li, B. Liu, C. Chen, Q. He, J.C. Crittenden, Smart ultrafiltration membrane fouling control as desalination pretreatment of shale gas fracturing wastewater: The effects of backwash water, *Environ. Int.* 130 (2019) 104869. <https://doi.org/10.1016/j.envint.2019.05.063>
- [96] S. Zhao, Z. Wang, A loose nano-filtration membrane prepared by coating HPAN UF membrane with modified PEI for dye reuse and desalination, *J. Mem. Sci.* 524 (2017) 214-224. <https://doi.org/10.1016/j.memsci.2016.11.035>
- [97] A.A., Saif, C.J. Wright, N. Hilal, Investigation of UF membranes fouling and potentials as pre-treatment step in desalination and surface water applications, *Desalination* 432 (2018) 115-127. <https://doi.org/10.1016/j.desal.2018.01.017>
- [98] F.M. Kafiah, Z. Khan, A. Ibrahim, R. Karnik, M. Atieh, T. Laoui, Monolayer graphene transfer onto polypropylene and polyvinylidene difluoride microfiltration membranes for water desalination, *Desalination* 388 (2016) 29-37. <https://doi.org/10.1016/j.desal.2016.02.027>
- [99] Y. Ibrahim, F. Banat, A.F. Yousef, D. Bahamon, L.F. Vega, S.W. Hasan, Surface modification of anti-fouling novel cellulose/graphene oxide (GO) nanosheets (NS) microfiltration membranes for seawater desalination applications, *J. Chem. Technol. Biotechnol.* 95 (2020) 1915-1925. <https://doi.org/10.1002/jctb.6341>
- [100] J. Shi, W. Wu, Y. Xia, Z. Li, W. Li, Confined interfacial polymerization of polyamide-graphene oxide composite membranes for water desalination, *Desalination* 441 (2018) 77-86. <https://doi.org/10.1016/j.desal.2018.04.030>
- [101] Z. Wan, Y. Jiang, Synthesis-structure-performance relationships of nanocomposite polymeric ultrafiltration membranes: A comparative study of two carbon nanofillers, *J. Mem. Sci.* (2020) 118847. <https://doi.org/10.1016/j.memsci.2020.118847>
- [102] Y. Orooji, F. Liang, A. Razmjou, G. Liu, W. Jin, Preparation of anti-adhesion and bacterial destructive polymeric ultrafiltration membranes using modified mesoporous

- carbon, Sep. Purif. Technol. 205 (2018) 273-283.
<https://doi.org/10.1016/j.seppur.2018.05.006>
- [103] C.E. Lin, J. Wang, M.-Y. Zhou, B.-K. Zhu, L.-P. Zhu, C.-J. Gao, Poly (m-phenylene isophthalamide) (PMIA): A potential polymer for breaking through the selectivity-permeability trade-off for ultrafiltration membranes, J. Mem. Sci. 518 (2016) 72-78. <https://doi.org/10.1016/j.memsci.2016.06.042>
- [104] X. Fang, J. Li, X. Li, S. Pan, X. Zhang, X. Sun, J. Shen, W. Han, L. Wang, Internal pore decoration with polydopamine nanoparticle on polymeric ultrafiltration membrane for enhanced heavy metal removal, Chem. Eng. J. 314 (2017) 38-49.
<https://doi.org/10.1016/j.cej.2016.12.125>
- [105] N. Ghaemi, A new approach to copper ion removal from water by polymeric nanocomposite membrane embedded with γ -alumina nanoparticles, Appl. Surf. Sci. 364 (2016) 221-228. <https://doi.org/10.1016/j.apsusc.2015.12.109>
- [106] F.S. Dehkordi, M. Pakizeh, M. Namvar-Mahboub, Properties and ultrafiltration efficiency of cellulose acetate/organically modified Mt (CA/OMMt) nanocomposite membrane for humic acid removal, Appl. Clay Sci. 105 (2015) 178-185.
<https://doi.org/10.1016/j.clay.2014.11.042>
- [107] S. Khezli, M. Zandi, J. Barzin, Fabrication of electrospun nanocomposite polyethersulfone membrane for microfiltration, Polym. Bull. 73 (2016) 2265-2286.
<https://doi.org/10.1007/s00289-016-1607-5>
- [108] Z. Li, W. Kang, H. Zhao, M. Hu, N. Wei, J. Qiu, B. Cheng, A novel polyvinylidene fluoride tree-like nanofiber membrane for microfiltration, Nanomaterials 6 (2016) 152. <https://doi.org/10.3390/nano6080152>
- [109] K. Fischer, M. Grimm, J. Meyers, C. Dietrich, R. Gläser, A. Schulze, Photoactive microfiltration membranes via directed synthesis of TiO₂ nanoparticles on the polymer surface for removal of drugs from water, J. Mem. Sci. 478 (2015) 49-57.
<https://doi.org/10.1016/j.memsci.2015.01.009>
- [110] A.K. Shukla, J. Alam, M. Rahaman, A. Alrehaili, M. Alhoshan, Ali Aldalbahi, A facile approach for elimination of electroneutral/anionic organic dyes from water using a developed carbon-based polymer nanocomposite membrane, Water Air Soil Pollut. 231 (2020) 1-16. <https://doi.org/10.1007/s11270-020-04483-4>