Chapter 2

Wastewater Treatment Using Membrane Technology

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http://dx.doi.org/10.5772/intechopen.76624

Abstract

Water contamination by heavy metals, cyanides and dyes is increasing globally and needs to be addressed as this will lead to water scarcity as well as water quality. Different techniques have been used to clean and renew water for human consumption and agricultural purposes but they each have limitations. Among those techniques, membrane technology is promising to solve the issues. Nanotechnology present a great potential in wastewater treatment to improve treatment efficiency of wastewater treatment plants. In addition, nanotechnology supplement water supply through safe use of modern water sources. This chapter reviews recent development in membrane technology for wastewater treatment. Different types of membrane technologies, their properties, mechanisms advantages, limitations and promising solutions have been discussed.

Keywords: wastewater, membrane technology, nanofiltration, forward osmosis, ultrafiltration, reverse osmosis

1. Introduction

Clean water is important for every living organism to withstand life, but due to rapid increase in growth population and industrialization, there is more demand for clean, safe and drinkable water [1]. About 97% of water is stored in oceans as salty water which is not good for human consumption or agricultural use, only less than 3% water on planet is available for drinking and agricultural use [2]. Most available water is highly contaminated by effluent from agricultural and industrial activity and cannot be consumed therefore water quality and quantity are the main problems that need to be solved [3]. Removal of contaminants/water pollutants is required as to avoid negative effects on the environment as well as human health [4].

Several techniques have been developed for treatment of wastewater; such methods include reverse osmosis [5] ion exchange [6] gravity [7] and adsorption [8] among others. Adsorption has been widely used to remove water contaminants due to its low cost, available of different adsorbents and easy operation. Different adsorbents that have been used include use of magnetic nanoparticles [9] activated carbon [10], nanotubes [11] and polymer nanocomposites [12]; these can remove different contaminants including heavy metals that are very harmful even at low concentrations. Even though adsorption can remove most of water pollutants, it has some limitations such as lack of appropriate adsorbents with high adsorption capacity and low use of these adsorbents commercially [13]. Hence there has been a need for more efficient techniques such as membrane technology. Membrane separation or treatment process mainly depends on three basic principles, namely adsorption, sieving and electrostatic phenomenon [14]. The adsorption mechanism in the membrane separation process is based on the hydrophobic interactions of the membrane and the solute (analyte). These interactions normally lead to more rejection because it causes a decrease in the pore size of the membrane [15]. The separation of materials through the membrane depends on pore and molecule size [16]. For this reason, various membrane processes with different separation mechanisms have been developed. These include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), forward osmosis (FO) and reverse osmosis (RO).

Therefore the aim of this chapter is review different membrane technology processes used for treatment of wastewater in the last 5 years (2014–2018). The advantages, challenges/limitations associated with the use of each membrane technology and possible solutions are also discussed briefly.

2. Challenges

Membrane processes such as MF, NF, UF and RO are currently used for water reuse, brackish water and seawater [17]. Polymer based membranes are mostly used membrane material but because polymers such as polysulfone and polyethersulfone, are hydrophobic [18], polymeric membranes are prone to fouling [19]. This leads to blockage of membrane pores and decrease membrane performance [20], also increases operation cost by demanding extra cleaning process. There are factors causing membrane fouling, such as deposition of inorganic components onto the surface membrane/solute absorption pore blocking, microorganism and feed chemistry [21]. This results to either reversible or irreversible membrane fouling [22]. Reversible fouling formed by attachment of particles on the membrane surface, irreversible which occurs when particles strongly attach the membrane surface and cannot be removed by physical cleaning. When there is a formation of strong matrix of the fouled layer with the solute during continuous filtration process will turn reversible fouling to irreversible fouling layer [23].

http://dx.doi.org/10.5772/intechopen.76624

3. Promising solutions

For polymeric membranes, surface modification of the polymer is essential; such surface modification includes grafting, blending and incorporation of nanomaterials such as TiO_2 [24]), ZnO [25], Al_2O_3 [26], carbon nanotubes [27] and graphene oxide [28]. Among these, graphene oxide membranes (GMs) are very promising in water treatment application such as desalination and wastewater treatment, due to their hydrophilic properties, flexibility and high mechanical strength; GMs have been reported to give wide range of pure water flux [28–32].

4. Membrane processes

4.1. Microfiltration (MF)

Microfiltration is a pressure driven process where separated compounds are 0.1–0.2 μm such as nanoparticles [33, 34]. It is regarded as the first pre-treatment of NF and RO membrane processes. MF removes little or no organic matter; however, when pre-treatment is applied, increased removal of organic material can occur. MF can be used as a pre-treatment to RO or NF to reduce fouling potential [35]. The main disadvantages of MF is that it cannot eliminate contaminants (dissolved solids) that are <1 mm in size. In addition, MF is not an absolute barrier to viruses. However, when used in combination with disinfection, MF appears to control these microorganisms in water [35].

4.2. Ultrafiltration (UF)

Ultrafiltration membrane process can separate compounds between 0.005 ≈ 10 μm which is between MF and RO [36]. UF membranes are highly prominent water filters with low energy consumption in removal of pathogenic microorganisms, macromolecules and suspended maters among others [37]. However, UF has some limitations including its inability to remove any dissolved inorganic substances from water and regular cleaning to maintain high pressure water flow [38]. Mocanu and others developed a synthetic procedure for hybrid ultrafiltration membrane for water treatment. They used wet-phase inversion method with polysulfone and graphene nanoplatelets modified with poly (styrene) to obtain their membranes. ZnO was deposited on one surface of the membrane with polymers that are soluble in water [39]. In the study reported by Igbinigun and others, the modified GO-membrane showed 2.6 times better flux recovery compared to the unmodified membrane and this shows that it is wise to modify membrane with GO to increase flux recovery. They used a simple method known as UV induced amination which has high flux UF membrane found to be resistant to organic fouling, and the resulting membrane can be applied in waste water treatment application. Incorporating hydrophilic materials onto the surface of these polymers will lead to more hydrophilic surface membrane [40].

4.3. Nanofiltration (NF)

NF is capable of removing ions that contribute significantly to the osmotic pressure hence allows operation pressures that are lower than those RO. For NF to be effective pre-treatment is needed for some heavily polluted waters; Membranes are sensitive to free chlorine. Soluble elements cannot be separated from water [41]. In the study reported by Yang and co-workers, PMIA/GO composite nanofiltration membranes were used for water treatment. The prepared composite membrane had greater hydrophilic surface which gave rise to high pure water flux compared to that of the pure polymer (PMIA). The results obtained showed high dye rejection and enhanced fouling resistance to bovine serum albumin (BSA) [42]. Xu and others reported NF membrane for textile wastewater treatment, the prepared membrane displayed good removal of heavy metal ions, common salts and dyes, showing high removal efficiency toward metal ions and cationic dyes [43]. Lin and others reported nanofiltration membranes for dye (Congo red and direct red) and salt rejection, the results showed high dye rejection and low salt rejection which shows the possibility of the salt reuse in FO.

4.4. Forward osmosis (FO)

FO is a natural occurrence where the solvent moves from a region of lower concentration to the region of higher concentration across a permeable membrane [44]. This method is found to be highly efficient with low rate production of brine and is well studied as it promise to solve water problems worldwide, however regeneration of the draw solution is highly expensive for desalination processes hence the use of nanofiltration or reverse osmosis for regeneration of draw solution [45].

4.5. Reverse osmosis (RO)

RO is pressure driven technique used to remove dissolved solids and smaller particles; RO is only permeable to water molecules. The applied pressure on RO must be enough so that water can be able to overcome the osmotic pressure. The pore structure of RO membranes is much tighter than UF, they convert hard water to soft water, and they are practically capable of removing all particles, bacteria and organics, it requires less maintenance [46]. Some disadvantages include the use of high pressure, RO membranes are expensive compared to other membrane processes and are also prone to fouling. In some cases, high level of pre-treatment is required [47]. RO has extremely small pores and able to remove particles smaller than 0.1 nm [48]. Huang and others, reported RO membranes coated with azide functionalized graphene oxide hence created smooth, antibacterial and hydrophilic membrane, which removed *Escherichia coli* and reduced BSA fouling [49].

5. Application of membrane technology for wastewater treatment

Zinadini and his group used zinc oxide nanoparticles to coat multiwalled carbon nanotubes (MWCNTs) which were later blended in polyethersulfone (PES) membrane. Incorporation

http://dx.doi.org/10.5772/intechopen.76624

of ZnO coated MWCNTs increased pure water flux due to the hydrophilic properties added. The results showed increase in antifouling properties as well as decrease in surface roughness brought by the embedded nanoparticle. ZnO/MWCNTs composite membrane showed greater dye removal compared to pure PES membrane [50]. Polymeric membranes in water treatment can reject up to 98% Cd ions through asymmetric polysulfone membrane [51]. Hybrid membranes are also used in removal of water contaminants as they introduce adsorptive capability, photocatalytic and antibacterial capabilities. This will lead to improved water flux and rejection value [52]. Aromatic polyamide is among other polymers that have been used in membrane industries. High pressure membrane includes tight UF, NF and RO, these are operated at high transmembrane pressure (>200 kPa) and low pressure membrane includes lose UF and MF. Usually fouling turn to occur when transmembrane increases, as to maintain flux or when there is decrease in flux [53].

Qiu and others have reported the use of hybrid microfiltration-osmosis membrane bioreactor to remove nitrogen and organic matter in municipal wastewater. Results showed decrease in fouling and reduced bacteria deposition [54]. In the study reported by Ochando-Pulido and others in olive mill wastewater and the rejection efficiency was 99.1% [55]. Microfiltration membrane has been applied in domestic wastewater and the amount percentage recovery of phosphorus was found to be 98.7% [56]. Combination of UF/NF/RO have been used in rendering plant wastewater (RPW) and the rand filtration was used as an effective pre-treatment for UF hence lowering membrane fouling [57]. Another form of membrane called membrane with a molecular weight cut-off (MWCO) was used to treat municipal and industrial wastewater, the obtained results showed complete resistance to irreversible fouling and high dye rejection [58]. UF and NF membranes have been used for waste stream purification also known as backwash water, which is obtained by washing filtration beds from swimming pool water system [59] (**Table 1**).

Matrix/pollutants	Membrane type	Performance	References
Oily water	MF	90.2% removal of organic additives	[60]
Olive mill wastewater	RO	COD rejection 97.5–99.1% and 24–32 $L\ h^{-1}\ m^{-2}$ permeate flux	[55]
Domestic wastewater	MF	>97% removal of total nitrogen and total phosphorus	[56]
Nitrogen and phosphorus in microalgae	FO and MF	86–99% removal efficiency for nitrogen 100% for phosphorus	[61]
Chlorophenol	RO	Improved unit performance	[62]
Municipal and industrial wastewater streams	membranes with a molecular weight cut-off (MWCO)	membranes showed complete resistance to irreversible fouling and high rejections of dyes	[58]

Table 1. Membrane applications.

6. Conclusions

This review provides detailed information about the current applications (2014–2018) of the membrane technology for treatment of wastewater. Generally, literature proved that different membrane technologies can be used to treat efficiently wastewaters from different activities. However, membrane fouling and membranes sensitivity to toxicity are the main limitations of the membrane technology. For this reason, Researchers has developed number of ways to overcome membrane technology. These ways include the incorporation of nanomaterials such as graphene oxide and nanometer sized metal oxides (zinc oxide), among others. In overall it can be concluded that membrane technology has been found to be a very promising method for wastewater treatment.

Acknowledgements

I would like to thank National Research Foundation (NRF, grant no. 99270) and Nanotechnology Innovation Centre (UJ Water Node) for providing financial support and the University of Johannesburg for making this study possible by making laboratory facilities available.

Conflict of interest

There is no conflict of interest.

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References

[1] Adeleye AS, Conway JR, Garner K, Huang Y, Su Y, Keller AA. Engineered nanomaterials for water treatment and remediation: Costs, benefits, and applicability. Chemical Engineering Journal. 2016;**286**:640-662

[2] Santhosh C, Velmurugan V, Jacob G, Jeong SK, Grace AN, Bhatnagar A. Role of nanomaterials in water treatment applications: A review. Chemical Engineering Journal. 2016; **306**:1116-1137

[3] Bethi B, Sonawane SH, Bhanvase BA, Gumfekar SP. Nanomaterials-based advanced oxidation processes for wastewater treatment: A review. Chemical Engineering and Processing: Process Intensification. 2016;**109**:178-189

[4] Moussa DT, El-Naas MH, Nasser M, Al-Marri MJ. A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. Journal of Environmental Management. 2017;**186**:24-41

[5] Yang Y, Pignatello JJ, Ma J, Mitch WA. Effect of matrix components on UV/H_2O_2 and UV/$S_2O_8^{2-}$ advanced oxidation processes for trace organic degradation in reverse osmosis brines from municipal wastewater reuse facilities. Water Research. 2016;**89**:192-200

[6] Beita-Sandí W, Karanfil T. Removal of both N-nitrosodimethylamine and trihalomethanes precursors in a single treatment using ion exchange resins. Water Research. 2017;**124**:20-28

[7] Carr SA, Liu J, Tesoro AG. Transport and fate of microplastic particles in wastewater treatment plants. Water Research. 2016;**91**:174-182

[8] Hatton TA, Su X, Achilleos DS, Jamison TF. Redox-based electrochemical adsorption technologies for energy-efficient water purification and wastewater treatment. In: Kamalesh K, Sirkar KK, editors. Separations Technology IX: New Frontiers in Media, Techniques, and Technologies. New Jersey Institute of Technology, USA Steven M. Crame, Rensselaer Polytechnic Institute, USA João G. Crespo, LAQV-Requimte, FCT-Universidade Nova de Lisboa, Caparica, Portugal Marco Mazzotti, ETH Zurich, Switzerland Eds, ECI Symposium Series. 2017. http://dc.engconfintl.org/separations_technology_ix/60

[9] Lai GS, Lau WJ, Goh PS, Ismail AF, Yusof N, Tan YH. Graphene oxide incorporated thin film nanocomposite nanofiltration membrane for enhanced salt removal performance. Desalination. 2016;**387**:14-24

[10] Saleh TA, Sarı A, Tuzen M. Optimization of parameters with experimental design for the adsorption of mercury using polyethylenimine modified-activated carbon. Journal of Environmental Chemical Engineering. 2017;**5**(1):1079-1088

[11] Saleh TA. Nanocomposite of carbon nanotubes/silica nanoparticles and their use for adsorption of Pb (II): From surface properties to sorption mechanism. Desalination and Water Treatment. 2016;**57**(23):10730-10744

[12] Lofrano G, Carotenuto M, Libralato G, Domingos RF, Markus A, Dini Gautam RK, Baldantoni D, Rossi M, Sharma SK, Chattopadhyaya MC. Polymer functionalized nanocomposites for metals removal from water and wastewater: An overview. Water Research. 2016;**92**:22-37

[13] Gaouar MY, Benguella B. Efficient and eco-friendly adsorption using low-cost natural sorbents in waste water treatment. Indian Journal of Chemical Technology (IJCT). 2016;**23**(3):204-209

[14] Padaki M, Murali RS, Abdullah MS, Misdan N, Moslehyani A, Kassim MA, Hilal N, Ismail AF. Membrane technology enhancement in oil–water separation. A review. Desalination. 2015;**357**:197-207

[15] Li K, Huang T, Qu F, Du X, Ding A, Li G, Liang H. Performance of adsorption pretreatment in mitigating humic acid fouling of ultrafiltration membrane under environmentally relevant ionic conditions. Desalination. 2016;**377**:91-98

[16] Zhao D, Yu Y, Chen JP. Treatment of lead contaminated water by a PVDF membrane that is modified by zirconium, phosphate and PVA. Water Research. 2016;**101**:564-573

[17] Erkanlı M, Yilmaz L, Çulfaz-Emecen PZ, Yetis U. Brackish water recovery from reactive dyeing wastewater via ultrafiltration. Journal of Cleaner Production. 2017;**165**:1204-1214

[18] Marino T, Blasi E, Tornaghi S, Di Nicolò E, Figoli A. Polyethersulfone membranes prepared with Rhodiasolv® Polarclean as water soluble green solvent. Journal of Membrane Science. 2018;**549**:192-204

[19] Ahmed F, Lalia BS, Kochkodan V, Hilal N, Hashaikeh R. Electrically conductive polymeric membranes for fouling prevention and detection: A review. Desalination. 2016;**391**:1-15

[20] Laohaprapanon S, Vanderlipe AD, Doma BT Jr, You SJ. Self-cleaning and antifouling properties of plasma-grafted poly(vinylidene fluoride) membrane coated with ZnO for water treatment. Journal of the Taiwan Institute of Chemical Engineers. 2017;**70**:15-22

[21] Zinadini S, Gholami F. Preparation and characterization of high flux PES nanofiltration membrane using hydrophilic nanoparticles by phase inversion method for application in advanced wastewater treatment. Journal of Applied Research in Water and Wastewater. 2016;**3**(1):232-235

[22] Ding Q, Yamamura H, Murata N, Aoki N, Yonekawa H, Hafuka A, Watanabe Y. Characteristics of meso-particles formed in coagulation process causing irreversible membrane fouling in the coagulation-microfiltration water treatment. Water Research. 2016;**101**:127-136

[23] Zhao F, Chu H, Zhang Y, Jiang S, Yu Z, Zhou X, Zhao J. Increasing the vibration frequency to mitigate reversible and irreversible membrane fouling using an axial vibration membrane in microalgae harvesting. Journal of Membrane Science. 2017;**529**:215-223

[24] Bet-Moushoul E, Mansourpanah Y, Farhadi K, Tabatabaei M. TiO_2 nanocomposite based polymeric membranes: A review on performance improvement for various applications in chemical engineering processes. Chemical Engineering Journal. 2016;**283**:29-46

[25] Tan YH, Goh PS, Ismail AF, Ng BC, Lai GS. Decolourization of aerobically treated palm oil mill effluent (AT-POME) using polyvinylidene fluoride (PVDF) ultrafiltration membrane incorporated with coupled zinc-iron oxide nanoparticles. Chemical Engineering Journal. 2017;**308**:359-369

[26] Garcia-Ivars J, Iborra-Clar MI, Alcaina-Miranda MI, Mendoza-Roca JA, Pastor-Alcañiz L. Surface photomodification of flat-sheet PES membranes with improved antifouling properties by varying UV irradiation time and additive solution pH. Chemical Engineering Journal. 2016;**283**:231-242

[27] Tijing LD, Woo YC, Shim WG, He T, Choi JS, Kim SH, Shon HK. Superhydrophobic nanofiber membrane containing carbon nanotubes for high-performance direct contact membrane distillation. Journal of Membrane Science. 2016;**502**:158-170

[28] Pandey RP, Shukla G, Manohar M, Shahi VK. Graphene oxide based nanohybrid proton exchange membranes for fuel cell applications: An overview. Advances in Colloid and Interface Science. 2016;**240**:15-30

[29] Chang Y, Shen Y, Kong D, Ning J, Xiao Z, Liang J, Zhi L. Fabrication of the reduced preoxidized graphene-based nanofiltration membranes with tunable porosity and good performance. RSC Advances. 2017;**7**(5):2544-2549

[30] Hu M, Zheng S, Mi B. Organic fouling of graphene oxide membranes and its implications for membrane fouling control in engineered osmosis. Environmental Science & Technology. 2016;**50**(2):685-693

[31] Safarpour M, Vatanpour V, Khataee A. Preparation and characterization of graphene oxide/TiO_2 blended PES nanofiltration membrane with improved antifouling and separation performance. Desalination. 2016;**393**:65-78

[32] Lai L, Xie Q, Chi L, Gu W, Wu D. Adsorption of phosphate from water by easily separable Fe_3O_4@ SiO_2 core/shell magnetic nanoparticles functionalized with hydrous lanthanum oxide. Journal of Colloid and Interface Science. 2016;**465**:76-82

[33] Qu X, Alvarez P, Werber JR, Deshmukh A, Elimelech M. The critical need for increased selectivity, not increased water permeability, for desalination membranes. Environmental Science & Technology Letters. 2016;**3**(4):112-120

[34] Xiaolei Q, Alvarez PJJ, Li Q. Applications of nanotechnology in water and wastewater treatment. Water Research. 2013;**47**(12):3931-3946

[35] Torki M, Nazari N, Mohammadi T. Evaluation of biological fouling of RO/MF membrane and methods to prevent it. European Journal of Advances in Engineering and Technology. 2017;**4**(9):707-710

[36] Qu F, Liang H, Zhou J, Nan J, Shao S, Zhang J, Li G. Ultrafiltration membrane fouling caused by extracellular organic matter (EOM) from *Microcystis aeruginosa*: Effects of membrane pore size and surface hydrophobicity. Journal of Membrane Science. 2014;**449**: 58-66

[37] Krüger R, Vial D, Arifin D, Weber M, Heijnen M. Novel ultrafiltration membranes from low-fouling copolymers for RO pretreatment applications. Desalination and Water Treatment. 2016;**57**(48-49):23185-23195

[38] Zhang L, Zhang P, Wang M, Yang K, Liu J. Research on the experiment of reservoir water treatment applying ultrafiltration membrane technology of different processes. Journal of Environmental Biology. 2016;**37**(5):1007

[39] Mocanu A, Rusen E, Diacon A, Damian C, Dinescu A, Suchea M. Electrochemical deposition of zinc oxide on the surface of composite membrane polysulfone-graphene-polystyrene in the presence of water soluble polymers. Journal of Nanomaterials. 2017;**2017**:11. Article ID: 1401503. DOI: 10.1155/2017/1401503

[40] Igbinigun E, Fennell Y, Malaisamy R, Jones KL, Morris V. Graphene oxide functionalized polyethersulfone membrane to reduce organic fouling. Journal of Membrane Science. 2016;**514**:518-526

[41] Wang N, Liu T, Shen H, Ji S, Li JR, Zhang R. Ceramic tubular MOF hybrid membrane fabricated through in situ layer-by-layer self-assembly for nanofiltration. AIChE Journal. 2016;**62**(2):538-546

[42] Yang M, Zhao C, Zhang S, Li P, Hou D. Preparation of graphene oxide modified poly (m-phenylene isophthalamide) nanofiltration membrane with improved water flux and antifouling property. Applied Surface Science. 2017;**394**:149-159

[43] Xu YC, Wang ZX, Cheng XQ, Xiao YC, Shao L. Positively charged nanofiltration membranes via economically mussel-substance-simulated co-deposition for textile wastewater treatment. Chemical Engineering Journal. 2016;**303**:555-564

[44] Ong CS, Al-anzi B, Lau WJ, Goh PS, Lai GS, Ismail AF, Ong YS. Anti-fouling double-skinned forward osmosis membrane with zwitterionic brush for oily wastewater treatment. Scientific Reports. 2017;**7**(1):6904

[45] Blandin G, Verliefde AR, Comas J, Rodriguez-Roda I, Le-Clech P. Efficiently combining water reuse and desalination through forward osmosis—Reverse osmosis (FO-RO) hybrids: A critical review. Membranes. 2016;**6**(3):37

[46] Wood AR, Justus K, Parigoris E, Russell A, LeDuc P. Biological inspiration of salt exclusion membranes in mangroves toward fouling-resistant reverse osmosis membranes. The FASEB Journal. 2017;**31**(1 Supplement):949-942

[47] Liu G, Han K, Ye H, Zhu C, Gao Y, Liu Y, Zhou Y. Graphene oxide/triethanolamine modified titanate nanowires as photocatalytic membrane for water treatment. Chemical Engineering Journal. 2017;**320**:74-80

[48] Yan HM, Cao CY, Bai G, & Bai W: Seawater desalination technology route and analysis of production capacity for large commercial nuclear power plant. In: International Conference Pacific Basin Nuclear Conference. Singapore: Springer; 2016. pp. 865-872

[49] Huang X, Marsh KL, McVerry BT, Hoek EM, Kaner RB. Low-fouling antibacterial reverse osmosis membranes via surface grafting of graphene oxide. ACS Applied Materials & Interfaces. 2016;**8**(23):14334-14338

[50] Zinadini S, Rostami S, Vatanpour V, Jalilian E. Preparation of antibiofouling polyethersulfone mixed matrix NF membrane using photocatalytic activity of ZnO/MWCNTs nanocomposite. Journal of Membrane Science. 2017;**529**:133-141

[51] Gao J, Sun SP, Zhu WP, Chung. Green modification of outer selective P84 nanofiltration (NF) hollow fiber membranes for cadmium removal. Journal of Membrane Science. 2016;**499**:361-369

[52] Li M, Wang W, Teng K, Xu Z, Li C, Shan M, Yanng C, Qian X, Jiao X. Manipulating F/O ratio of fluorinated graphene oxide to improve permeability and antifouling properties of poly (vinylidene fluoride) hybrid membranes. Journal of Nanoscience and Nanotechnology. 2017;**17**(12):8935-8945

[53] Jia Z, Hao S, Liu Z. Synthesis of $BaSO_4$ nanoparticles with a membrane reactor: Parameter effects on membrane fouling. Journal of Membrane Science. 2017;**543**:277-281

[54] Qiu G, Zhang S, Raghavan DSS, Das S, Ting YP. The potential of hybrid forward osmosis membrane bioreactor (FOMBR) processes in achieving high throughput treatment of municipal wastewater with enhanced phosphorus recovery. Water Research. 2016;**105**:370-382

[55] Ochando-Pulido JM, Stoller M, Víctor-Ortega MD, Martínez-Férez A. Analysis of the fouling build-up of a spiral wound reverse osmosis membrane in the treatment of two-phase olive mill wastewater. Chemical Engineering Transactions. Italian Association of Chemical Engineering-AIDIC. 2016;**47**:403-408

[56] Zuo K, Chen M, Liu F, Xiao K, Zuo J, Cao X, Zhang X, Liang P, Huang X. Coupling microfiltration membrane with biocathode microbial desalination cell enhances advanced purification and long-term stability for treatment of domestic wastewater. Journal of Membrane Science. 2018;**547**:34-42

[57] Racar M, Dolar D, Špehar A, Košutić K. Application of UF/NF/RO membranes for treatment and reuse of rendering plant wastewater. Process Safety and Environmental Protection. 20171;**05**:386-392

[58] Bengani-Lutz P, Zaf RD, Culfaz-Emecen PZ, Asatekin A. Extremely fouling resistant zwitterionic copolymer membranes with ~1 nm pore size for treating municipal, oily and textile wastewater streams. Journal of Membrane Science. 2017;**543**:184-194

[59] Łaskawiec E, Madej M, Dudziak M, Wyczarska-Kokot J. The use of membrane techniques in swimming pool water treatment. Journal of Ecological Engineering. 2017;**18**(4):130-136

[60] Chang Q, Zhou JE, Wang Y, Liang J, Zhang X, Cerneaux S, Wang X, Zhu Z, Dong Y. Application of ceramic microfiltration membrane modified by nano-TiO_2 coating in separation of a stable oil-in-water emulsion. Journal of Membrane Science. 2014;**456**: 128-133

[61] Praveen P, Heng JYP, Loh KC. Tertiary wastewater treatment in membrane photobioreactor using microalgae: Comparison of forward osmosis & microfiltration. Bioresource Technology. 2016;**222**:448-457

[62] Al-Obaidi MA, Li JP, Kara-Zaitri C, Mujtaba IM. Optimisation of reverse osmosis based wastewater treatment system for the removal of chlorophenol using genetic algorithms. Chemical Engineering Journal. 2017;**316**:91-100