IOP Conference Series:
Materials Science and
Engineering

Performance of mixed matrix nanofiltration membranes in wastewater treatment: A review

Performance of mixed matrix nanofiltration membranes in wastewater treatment: A review

O. Agboola[1,3*], O.S.I. Fayomi[2], B.A. Oni[1], A.O. Ayeni[1], E.R. Sadiku[3], A.P.I. Popoola[3], L. Moropeng[3], S.T. Adegbola[4], D. Daramola[5]

[1]Department of Chemical Engineering, Covenant University, Ota, Nigeria
[2]Department of Mechanical Engineering, Covenant University, Ota, Nigeria
[3]Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa
[4]Department of Mechanical Engineering, Tshwane University of Technology, Pretoria, South Africa
[5]Department of Biomedical Engineering, Bells University of Technology, Ota, Ogun State, Nigeria
Corresponding Author: funmi2406@gmail.com; oluranti.agboola@covenantuniversity.edu.ng

Abstract

Water covered close to 70% of the Earth's surface; however, it is a struggle to access 3% of it as freshwater, suitable for human intake. The shortage of water has become a global issue due to climate change, pollution and the demand of growing freshwater. The fabrication of high performance and antifouling nanofiltration membranes are of utmost importance as a result of their capability of treating contaminated water and to also regulate the quality of freshwater. However, there is need for improvement in the fabrication of membrane using different nanofillers to produce mixed matrix membranes (MMMs). Mixed matrix nanofiltration membranes with nanofillers were reviewed for different applications.

Keyword: Nanofiltration, mixed matrix membranes, nanoparticles, carbon nanotubes

1. Introduction

Water is not equally dispersed after a while and more water is wasted, contaminated and not managed in a sustainable way; which has led to loosing thousands of people yearly due to the shortage of water. Hence, shortage of water have pronounced effect on human health, growth of socio-economic and the surroundings [1-4]. Nanofiltration membranes (NF) could be utilized for diverse water and wastewater treatment industries due to their low cost for the removal of ions and organic substances. Present-day investigations in the field of nanofiltration technology is mainly apprehensive about the improvement of the performance of NF membranes in order to minimize fouling and reduce energy requirements of water treatment processes that is already in working operation. Researchers have presented ultra-modern concepts and design of developing new membranes with an aim of obtaining efficient performance they are applied in separation processes [5]. Several procedures utilized in fabricating nanofiltration membranes exist; nonetheless, the option of a pertinent method is contingent on the type of material and the application they will be used for. The properties of membrane may relatively be controlled, via proper selection of the preparation technique and working with the main process conditions.

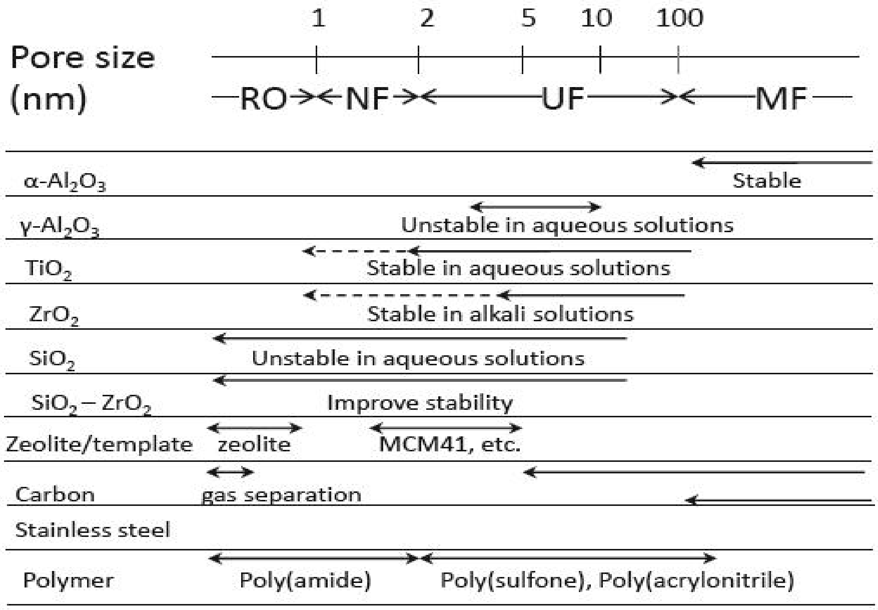
Researchers have attempted to enhance the performance of NF, especially to upsurge the permeate flux and lessen the resistance of membrane through experiments with diverse membrane materials and configuration. Thin film composite membranes are inter-facially polymerized on top of a microporous substrate and they have been commercially successful with regards to their applications in industries as a result of their capability in the optimization of the selectivity and permeability of individual stratum [6-9]. It has been recently revealed that the integration of nanomaterials suchlike electrospun nanofibrous membrane layers to typical thin film composite membranes resulted in an increased permeate flux. The result obtained is due to the essential properties of electrospun nanofibrous membrane that favor the flux; consequently, there was reduction in membrane fouling and the cost of the pre-treatment energy [10]. Electrospun nanofibrous membranes possess exceptional properties like well coordinated pore configuration, high surface area to volume ratio, low trans-membrane pressure, high porosity, excellent mechanical properties and enhance permeability of water. These properties offers a main impact in the process of water treatment. These nanofibers have been used for several water treatment utilizations, and are dependent on thickness, porosity, and surface roughness [11]. Apart from the addition of electrospun nanofibrous membranes to conventional thin film composite membranes, nanofiltration membranes are fabricated with the integration of nanomaterials such nanoparticles, carbon nanotubes, nanoporous ceramics and nano-sponges. This review aim at giving an overview of mixed matrix membranes using nanofillers for wastewater treatment.

2. Mixed matrix nanofiltration membranes with nanofillers

Up to this present time, the advancement researchers have attempted on material science, for the improvement of membranes is contingent on nanocomposites. The overabundance of diverse kinds of nanomaterials has practically presented infinite high-tech benefits with regards to the variation and optimizing the current novel membrane for present-day desalination plants [12]. The assimilation of nanofillers such as nanoparticles within polymer matrix has offered an innovative method for fabrication of membranes with boosted permeability, selectivity in an elevated manner and enhanced properties for anti-fouling [13]. Mixed matrix membranes (MMMs) are aimed in taking the benefit of low cost simple method of preparing organic polymeric membranes that possess enhanced mechanical strength with effective working properties of inorganic materials [14]. Application of nanoparticles in the fabrication of membranes provides the capability to make membrane with preferred structure and their functionalities; this gives a practical level of control over membrane fouling [15, 16]. Figure 1 shows the dynamic of preparing functionalized nanofiltration membranes that will result to high performances. Furthermore, the integration of nanofillers in nanofiltration membranes should enhanced the properties of MMMs. Hence, MMMs should have high specific surface area, exceptional mechanical stability and physicochemical properties for the purpose of improving water-permeation of the membrane. Table 1 shows the stability of nano-materials used for synthesizing NF membranes for the treatment of contaminated water. The unique properties of these nanomaterials have resulted to their use in diverse applications, especially in the fabrication of commercial filtration membranes that is cost effective. This may perhaps, greatly cut down the cost of clean water production.

IOP Conf. Series: Materials Science and Engineering 1107 (2021) 012007 doi:10.1088/1757-899X/1107/1/012007

Table 1: Stability of polymers/nanomaterials in aqueous/alkali solutions [17]



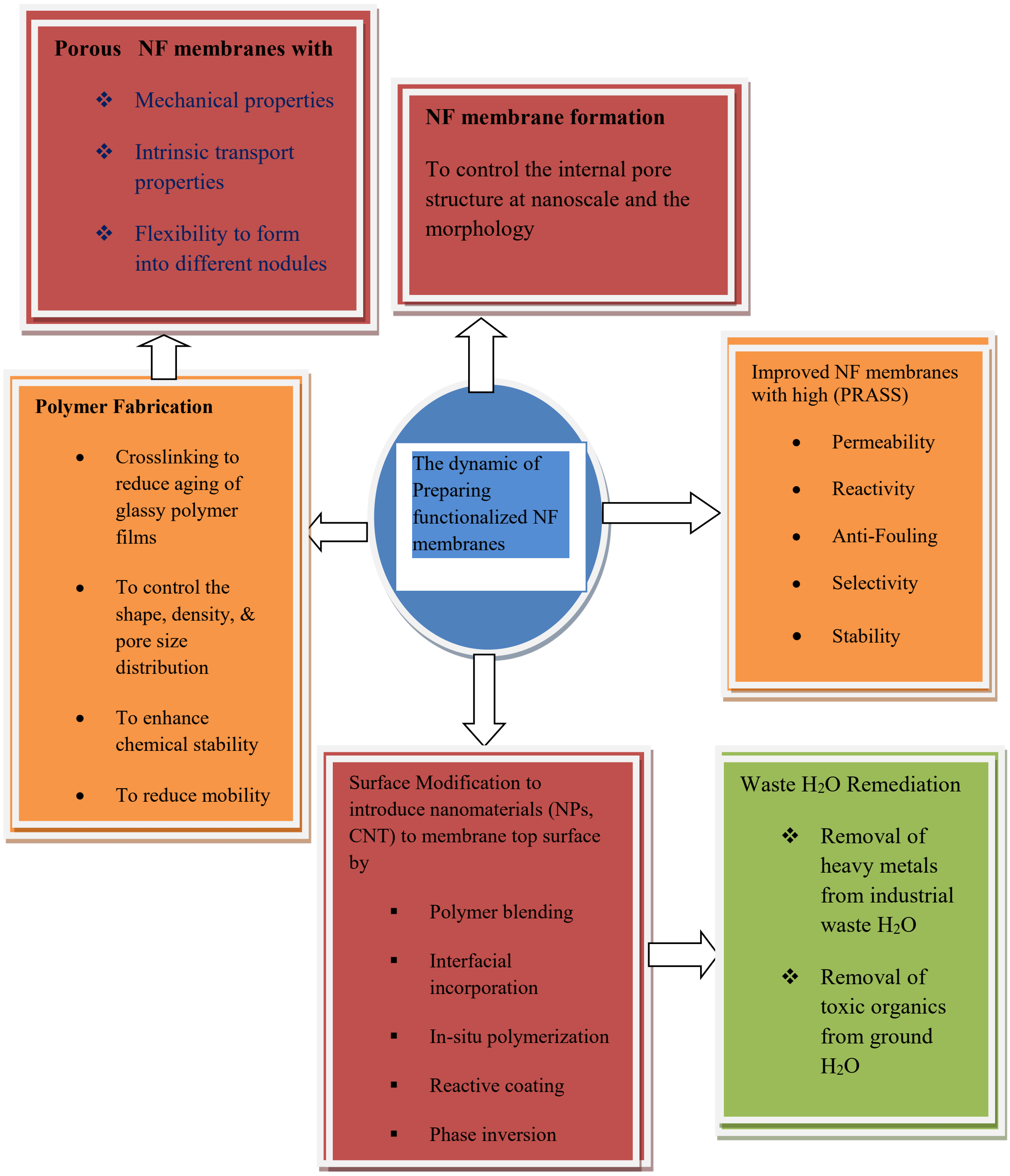


Figure 1: Schematic design of the dynamic of preparing nanofiltration membranes for excellent performance

2.1 Titanium dioxide (TiO_2) Nanofiltration MMM for wastewater treatment

TiO_2 is among one of the nanoparticles that is mostly utilized in synthesizing MMMs. TiO_2 has severally been employed in the fabrication membranes for the purpose of enhancing the surface properties and structure modifications. This is because it has the capability of degrading natural organic matters, creating additional structures that are hydrophilic, and decomposing bacterial cells. [18]. TiO_2 nanoparticle has positively stimulated substantial reaction for the synthesis of nanofiltration membranes with regards to increase in flux and improved fouling resistance. Extensive research on the prospective application of TiO_2 nanoparticles for the reduction of membrane fouling has been conducted [19-21]. This involves the application of a nonporous coating of Titania over membrane surface. This has helped in resisting the internal fouling of the membrane as a result of the non-porosity of the coating. In addition, the super-hydrophilic nature of Titania offers resistance to fouling via the deceasing of adhesion of waste on the surface of the membrane [22]. However, different methods might be employed in the synthesis of mixed matrix nanofiltration membranes integrated with TiO_2.

Peyravi et al. [23] developed an innovative thin film nanocomposite (TFN) solvent resistant NF membranes via interface layer integration of functionalized TiO_2 over a porous polyimide support; formerly coated by polyethyleneimine. From their study, Fourier transform infrared spectroscopy analysis depicted that the dispersion or stabilization of agents were covalently or physically bonded to the TiO_2. Furthermore, exceptional stability in organic and aggressive solvents was observed as a result of the limitation of chain mobility found in the presence of rigid TiO_2 domains. Flux was enhanced together with high selectivity of the removal of dyes for TFN-SRNF membrane. Venkatesh et al. [24] investigated the removal of oil from water in emulsion by employing polyvinylidene difluoride mixed matrix nano-filtration membranes incorporated with 1D-PANI/TiO_2 NFs. In their study, 1-D PANI/TiO_2 nanofibers were integrated into polyvinylidene difluoride mixed matrix membranes for the separation of oil and water droplets from oily wastewater. From their study, there was an increase in pure water flux; from 80 to 132 L m^{-2} h^{-1}. This is an indicator that there was an impact in addition of the 1D PANI/TiO_2 NFs to polyvinylidene difluoride. From the mixed matrix membranes fabricated, PT-4 displayed the highest retention efficiency (99%) of oil at 5 bar. Khorshidi et al. [25] developed a novel methodology for fabricating robust thin film nanocomposite reverse osmosis membrane. This novel method involves the concurrent fabrication and surface functionalization of TiO_2 NPs in an organic solvent (heptane) through biphasic solvothermal reaction. The membranes fabricated were used for the treatment of high-temperature streams made of biological materials and these membranes demonstrated better thermal stability and anti-biofouling properties. Koutahzadeh et al. [26] studied the performance of a hybrid ultraviolet/hydrogen peroxide–mixed matrix membranes system for the removal of an azo dye, known as acid black, from a wastewater purification process. 270 ($L/[m^2 \cdot h]$) permeation, 29% flux decline, 90% total organic carbon retention, 99% decolorization, and 99% flux recovery ratio were attained using hybridized process of ultraviolet/hydrogen peroxide-polysulfones /TiO_2/multi walled carbon nanotube-mixed matrix membrane.

2.2 Aluminum oxide (Al_2O_3) Nanofiltration MMM for wastewater treatment

Aluminum oxide (Al_2O_3) is among the stable inorganic nanoparticles utilized in preparing membranes on the account of increasing the performance membranes. This nanoparticle is not expensive, non-toxic, highly abrasive and resistant. Al_2O_3 nanoparticles was integrated into polyvinylidene difluoride (PVDF) membrane by utilizing dimethyl acetamide as solvent [27]. The influence of the concentration of Al_2O_3 in the polymer dope on the permeation properties, structures of membrane and performances of membrane for antifouling were studied. The results obtained pointed to the fact that Al_2O_3-polyvinylidene difluoride composite membranes showed weighty changes in surface and inherent properties owing to the addition of nanoparticles [28]. This suggested that a positive influence occur on reducing bio-fouling. Saleh and Gupta [29] synthesized polyamide (PA) nanocomposite membrane with the integration of alumina nanoparticles (which was homogeneously distributed) through in situ interfacial polymerization. It was observed that the membrane performed better than pristine membrane, with improved permeate flux and salt rejection. Bagheripour et al. [30] prepared polyvinylchloride-based nanocomposite NF membranes via the utilization of sodium dodecyl sulfate as additive. In addition, Al_2O_3 nanoparticles was used as inorganic filler and dimethylacetamide/tetrahydrofuran as solvents through phase inversion technique. Khalili et al. [31] prepared bi-layered γ-Al_2O_3–TiO_2 NF membranes based on α-alumina supports for the removal of chloride ion. Compression was used in preparation of the supports and sol–gel dip-coating for the top-layer formation. Their results showed that the calcination temperature (600°C) results in different crystal structures including the brookite phase of TiO_2, the γ phase of Al_2O_3, and a combined phase of aluminium–titanium oxides Filtration experiments confirmed the smooth rejection behaviour in an extended pH range because of the dual-layer structure with different isoelectric points (IEPs). Their results showed a higher rejection in the alkaline pH range over the acidic region.

2.3 Zinc oxide (ZnO) Nanofiltration MMM for wastewater treatment

ZnO is a semiconductor having an extensive bandgap comparable to TiO_2 [32]. It is highly reactive with higher surface area, chemical stability, and non-toxic nature. It is an imperative multifunctional semiconductor material, remarkably significant for photo-catalysis application and it is also used as anti-bacterial materials. This is on the account of its outstanding electrical, optical, chemical and mechanical properties [33]. Embedding ZnO nanoparticles in membrane matrix could result into a steady system, making their physical properties to be connected to their size and having the chemical activity to be linked with their ease of use in the membrane. This will make the application of nano-size scale ZnO integrated in membranes full of promise for the advancement of cost effective and anti-fouling membrane technology [34]. Balta et al. [34] investigated the performance of fabricated MMMs integrated with ZnO nanoparticles. The novel membrane integrated with ZnO nanoparticles exhibited enhanced membrane topographies. Hence, the membrane performed much better than the neat membranes with regards to permeability, rejection of dye and resistance to fouling.

2.3 Carbon nanotube Nanofiltration MMM for wastewater treatment

A practical strategy of reducing fouling in wastewater treatment is the fabrication of advanced membrane materials that will possess antifouling properties [35]. Nowadays, carbon nanotubes (CNTs) have found utilizations in the field of nanofiltration membrane technology based on their inherent electrical, thermal, mechanical and separation properties. Among the utmost extensively studied artificial nanomaterials, single-walled carbon nanotubes (SWNTs) have found wider applications as a result of their uncommon basic properties. They are sized in nanometre range, with needle like cylinder prepared via a rolled-up graphene sheet to transform to a graphical shell [36]. A vital means used for tailoring the interactivities of SWNTs with their milieu is functionalization [37]. This kind of functionalization could be noncovalent such as coatings of surfactants, synthetic polymers, or biopolymers [38] or covalent, attained via chemical reactions responsible for linking addends to the nanotube sidewall carbon atoms [39, 40]. Carbon nanotube with a number of concentric graphite shells is termed multi-walled carbon nanotubes (MWCNTs) [41]. The distinctive properties of these carbon nanotubes are their exceptionally high separations;

IOP Conf. Series: Materials Science and Engineering 1107 (2021) 012007 doi:10.1088/1757-899X/1107/1/012007

inner diameter at nano and atomic scaled, smooth, hydrophobic graphitic walls. MWCNTs have appeared to be a novel nano membrane material (NMM) for the separation of liquid and gas because of their large surface area [42]. CNT with well-established framework have the capacity to function as robust pores in membranes used for the applications of water desalination and decontamination [43]. The CNT frictionless channels with specifically controlled pore entrances might at the same time aid the fast movement of water molecules and provide excellent capability foe the rejection of salt [12]. For example, the hollow CNT structure affords frictionless movement of water molecules; hence, allow its suitability for the advancement of high flux separation methods [44]. Apposite pore diameters could create energy barricades at the channel entrances, leading to salt rejection and allowing permeation of water via nanotube hollows [45]. CNT pores can also be modified for the purpose of selectively sensing and rejecting ions [46].

Nano-sized particles and CNTs are considered excellent materials used as additives for polymeric membrane due to their high hydrophilicity, good chemical stability and high surface area. Nanocomposite nanofiltration membranes include a composite of carbon nanotubes coated or chemically bonded with metal oxide nanoparticles. They could be taken into consideration as a novel group of filtration materials made of mixed matrix membranes with high surface-functionality [47]. Vatanpour et al. [48] synthesized multi walled carbon nanotubes coated by anatase TiO_2 nanoparticles through the precipitation of $TiCl_4$ precursor on the acid oxidized multi walled carbon nanotubes in order to be employed in the synthesis of nanocomposite polyethersulfone (PES) membranes. Ultraviolet (UV) irradiation on the TiO_2 contributed to the formation of holes and electrons. The electrons generated would reduce Ti (IV) cations to the Ti (III) state and the holes will oxidized O_2^- anions. Oxygen atoms are therefore removed and a group of oxygen vacancies are made on the surface. As a result, water molecules from the surroundings would take up the vacancy and the OH groups adsorbed would contribute to the formation of membrane surface with higher hydrophilicity. Additionally, the radicals produced can avoid the proteins deposition thus reduced membrane surface fouling. These researchers discovered that TiO_2 nanoparticles used possessed low agglomeration during the application as the nanoparticles exhibited good compatibility with the polymeric components. Incorporation of these additives into the PES membrane matrix led to an increased pure water flux, higher hydrophilicity, better anti-biofouling and decreased membrane surface roughness. Vatanpour and some group [49] synthesized flat sheet asymmetric amine-functionalized MWCNTs/polysulfone nanocomposite NF membranes with diverse nanofiller contents via the phase inversion technique. The membranes were assessed with respect to pure water flux, static protein adsorption and bovine serum albumin filtration. The authors found that the hydrophilicity and pure water flux of the membranes were improved with the upsurge of NH_2-MWCNTs dosages. Sumisha et al. [50] fabricated nanofiltration membranes by using functionalized titanate nanotubes via phase inversion process. The neat membrane and MMMs were fabricated by employing polyethylenimine and TiO_2 particles. The retention performances of NaCl, K_2SO_4 and $CaCl_2$ ions increased. CNTs were also integrated into alumina/polyethersulfone hollow fibre membranes for the purpose of improving the mechanical property and the effectiveness of water treatment [51]. It was observed that the integration of CNTs could significantly hinder large surface pores formation, leads to reduction in void size of the support layers and enhance the porosity and pore connection of alumina/polyethersulfone membranes. Hence, enhanced flux and rejection.

3. Conclusion

The stage of nanotechnology development has totally offered diverse innovative functional materials that have the capacity to be used for the creation of advanced properties for nanofiltration membranes in water treatment. The progress of developing innovative materials with improved properties is a very important issue for the development of the nanofiltration membranes. With several use of integration of nanomaterials in nanofiltration membranes, mixed matrix membranes are being developed for creating advanced properties required for wastewater treatment.

Acknowledgement
The authors wish to acknowledge the financial support offered by Covenant University in actualization of this research work for publication.

References

[1] Agboola, O., Maree, J., & Richard, M. (2014). Characterization and performance of nanofiltration membranes. Environmental Chemistry Letters, 12. 241-255.
[2] Agboola, O., Sanni, E.S., Oyekunle, D.T., Ayeni, A.O., Oni, B.A., Ayoola, A., Popoola, P., & Sadiku, R. (2019). Assessment of the Performance of Osmotically Driven Polymeric Membrane Processes. International Conference on Engineering for Sustainable World, Journal of Physics: Conference Series, 1378**,** 032047.

[3] Agboola, O., Kolesnikov, A., Sadiku, E.R., Maree, J.P., Mbaya, R., & Sanni, E.S. (2019). Model assessment of a nanofiltration membrane for the removal metal ions from simulated wastewater. International Conference on Engineering for Sustainable World, Journal of Physics: Conference Series, 1378**,** 032048.
[4] Agboola, O., Popoola, P., Sadiku, E.R., Sanni, E.S., Fayomi, S.O., & Fatoba, O.S. (2020). Nanotechnology in Wastewater and the Capacity of Nanotechnology for Sustainability: In: Environmental chemistry for sustainable world 27, Environmental Nanotechnology, Volume 3. Springer Nature, Switzerland
[5] Hilal, N., Ismail, A.F., & Wright, C. (2015). Membrane Fabrication. CRC Press, Taylor and Francis Group, USA, p. 1.
[6] Mioa, J., Chen, G., Goa, C., & Dong, S. (2008). Preparation and characterization of N,O-carboxymethyl chitosan/Polysulfone composite nanofiltration membrane crosslinked with epichlorohydrin. Desalination, 233, 147-456.
[7] Akbari, A., Homayoonfal, M., & Jabbari, V. (2010). Fabrication of new photografted charged thin film composite (TFC) nanofiltration membrane applied to waste water treatment: Effect of filtration parameters on the rejection of salts and dyes. Journal of Waste Water Treatment Analysis, 1(2), 1-9.
[8] Misdan, N., Lau, W.J., Ismail, A.F., & Mathuura, T. (2013). Formation of thin film composite nanofiltration membrane: Effect of polysulfone substrate characteristics. Desalination, 329, 9-18.
[9] Lau, W.J., Ismail, A.F., Goh, P.S., Hilal, N., & Ooi, B.S. (2015). Characterization methods of thin film composite nanofiltration membranes. Separation Purification Reviews 44(2), 135-156.
[10] Subramanian, S., & Seeram, R. (2013). New direction is nanofiltration applications-Are nanofibers the right materials as membrane in desalination. Desalination, 308(2), 198-208.
[11] Nasreen, S.A.A.N., Subramanian, S., Nizar, S.A., Balamurugan, R., & Seeram, R. (2013). Advancement in electrospun nanofibrous membranes modification and their application in water treatment. Membrane, 3, 266-284.

IOP Conf. Series: Materials Science and Engineering 1107 (2021) 012007 doi:10.1088/1757-899X/1107/1/012007

[12] Goh, P.S., Ismail, A.F., Hilal, N. (2016). Nano-enabled membranes technology: Sustainable and revolutionary solutions for membrane desalination? Desalination, 380, 100-104

[13] Bano, S., Mahmood, A., Kim, S-J., & Lee, K-H. (2015). Graphene oxide modified polyamide nanofiltration membrane with improved flux and antifouling properties. Journal of Materials Chemistry A, 3, 2065-2071.

[14] Pendergast, M.M., & Hoek, E.M.V. (2011). A review of water treatment membrane nanotechnologies. Energy and Environmental Science, 4, 1964-1971.

[15] Cortalezzi, M.M., Rose, J., Wells, G.F., Bottero, J.Y., Wiesner, M.R., & Barron, A.R. (2003). Ceramic membranes derived from ferroxane nanoparticles: a new route for the fabrication of iron oxide ultrafiltration membranes. Journal of Membrane Science, 227, 207-217.

[16] Jones CD, Fidalgo M, Wiesner MR, Barron AR (2001) Alumina ultrafiltration membranes derived from carboxylate–alumoxane nanoparticles. Journal of Membrane Science, 193, 175-184.

[17] Tsuru, T. (2001). Inorganic porous membranes for liquid phase separation. Separation and Purification Methods, 30(2), 191-220.

[18] Mollahosseini, A., & Rahimpour, A. (2014). Interfacially polymerized thin film nanofiltration membranes on TiO_2 coated polysulfone substrate. Journal of Industrial and Engineering Chemistry, 20, 1261-1268.

[19] Lee, H.S., Im, S.J., Kim, J.H., Kim, H.J., Kim, J.P., & Min. B.R. (2008). Polyamide thin-film nanofiltration membranes containing TiO_2 nanoparticles. Desalination, 219(1), 48-56.

[20] Sotto, A., Boromand, A., & Balta, S. (2011). Nanofiltration membranes enhanced with TiO_2 nanoparticles: a comprehensive study. Desalination Water Treatment, 34, 179-783.

[21] Vatanpour, V., Madaeni, S.S., Moradiane, R., Zinadini, S., & Astinchap, B. (2012). Novel antibiofouling nanofiltration polyethersulfone membrane fabricated from embedding TiO_2 coated multiwalled carbon nanotubes. Separation Purification Technology, 90, 69-82.

[22] Drazevic, E., Kosudic, K., Dananic, V., & Pavlovic, D.M. (2013). Coating layer effect on performance of thin film nanofiltration membrane in removal of organic solutes. Separation Purification Technology, 118(30), 530-539.

[23] Peyravi, M., Jahanshahi, M., Rahimpour, A., Javadi, A., & Hajavi, S. (2014). Novel thin film nanocomposite membranes incorporated with functionalized TiO_2 nanoparticles for organic solvent nanofiltration. Chemical Engineering Journal, 241, 155-166.

[24] Venkatesh, K., Arthanareeswaran, G., & Bose, A.C. (2016). PVDF mixed matrix nano-filtration membranes integrated with 1D-PANI/TiO_2 NFs for oil–water emulsion separation. RSC Advances, 6, 18899-18908

[25] Khorshidi, B., Biswas, I., Ghosh, T., Thundat, T., & Sadrzadeh, M. (2018). Robust fabrication of thin film polyamide-TiO_2 nanocomposite membranes with enhanced thermal stability and anti-biofouling propensity. Scientific Reports, 8, 784, 1-10.

[26] Koutahzadeh, N., Esfahani, M.R., & Arce, P.E. (2016). Sequential use of UV/H_2O_2 - (PSF/TiO_2/MWCNT) Mixed matrix membranes for dye removal in water purification: Membrane permeation, fouling, rejection and decoloration. Environmental Engineering Science, 33(6), 430-440.

[27] Yan, L., Li YS, Xiang CB (2005) Preparation of poly (vinylidene fluoride) (PVDF) ultrafiltration membrane modified by nano-sized alumina (Al_2O_3) and its antifouling research. Polymer, 46, 7701-7706.

[28] Wang, X-O., Li, X-Y., & Shih, K. (2011). In situ embedment and growth of anhydrous and hydrated aluminum oxide particles on polyvinylidene fluoride (PVDF) membranes. Journal of Membrane Science, 368, 134-143.
[29] Saleh, T.A., & Gupta, V.K. (2012). Synthesis and characterization of alumina nanoparticles polyamide membrane with enhanced flux rejection performance. Separation and Purification Technology, 89, 245-251.
[30] Bagheripour, E., Moghadassi, A.R., & Hosseini, S.M. (2015). Fabrication of polyvinyl chloride based nanocomposite nanofiltration membrane: investigation of SDS/Al_2O_3 nanoparticle concentration and solvent ratio effects. Asia-Pacific Journal of Chemical Engineering, 10(5), 791-798.
[31] Khalili, M., Sabbaghi, S., & Zerafat, M.M. (2015). Preparation of ceramic γ-Al_2O_3-TiO_2 nanofiltration membranes for desalination. Chemical Papers, 69(2), 309-315.
[32] Hairom, N.H.H., Mohammad, A.W., Ng, L.Y., & Kadhum, A.A.H. (2015). Utilization of self-synthesized ZnO nanoparticles in MPR for industrial dye wastewater treatment using NF and UF membrane. Desalination and Water Treatment, 54, 944-955.
[33] Hu, W., Shiyan, C., Zhou, B., & Wang, H. (2010). Facile synthesis of ZnO nanoparticles based on bacterial cellulose. Material Science and Engineering B, 170, 88-92.
[34] Balta, S., Sotto, A., Luis, P., Benea, L., Van der Bruggen, B., & Kim, J. (2012). A new outlook on membrane enhancement with nanoparticles: The alternative of ZnO. Journal of membrane Science, 389, 155-161.
[35] Huang, J., Wang, H., & Zhang, K. (2014). Modification of PES membranes with Ag-SiO_2: Reduction of biofouling and improvement of filtration performance. Desalination 336, 8-17.
[36] Goh, K., Setiawan, L., Wei, L., Jiang, W., Wang, R., & Chen, Y. (2013). Fabrication of novel functionalized multiwalled carbon nanotube immobilized hollow fiber membranes for enhanced performance in forward osmosis process. Journal of Membrane Science, 446, 244-254.
[37] Hirsch, A., & Vostrowsky, O. (2005). Functionalization of carbon nanotubes. Topic in Current Chemistry, 245, 193-237.
[38] Moore, V.C., Strano, M.S., Haroz, E.H., Hauge, R.H., & Smalley, R.E. (2003). Individually suspended single-walled carbon nanotubes in various surfactants. Nano Letters, 3, 1379-1382.
[39] Liang, F., Alemany, L.B., Beach, J.M., & Billups, W.E. (2005). Structure analyses of dodecylated single-walled carbon nanotubes. Journal of America Chemical Society, 127, 13941-13948.
[40] Chattopadhyay, J., Sadana, A.K., Liang, F., Beach, J.M., Yunxuan, X., Hauge, R.H., & Billups, W.E. (2005). Carbon Nanotube Salts. Arylation of single-wall carbon nanotubes. Organic Letters, 7, 4067-4069.
[41] Noy, A., Park, H.G., Fornasiero, F., Holt, J.K., Grigoropoulos, C.P., & Bakajin, O. (2007). Nanofluidics in carbon nanotubes, Nano Today, 2, 22-29.
[42] Aroon, M.A., Matsuura, T., & Ismail, A.F. (2012). A comparison between β-Cyclodextrin and Chitosan as Soft Organic Materials for Surface Modification of MWCNTs. International Journal Nanoscience and Nanotechnology, 8(2), 71-78.
[43] Elimelech, M., & Phillip, W.A. (2011). The future of seawater desalination: energy, technology, and the environment. Science, 333(6043), 712-717.
[44] Das, R., Ali, Md. E., Hamid, S.B.A., Ramakrishna, S., & Chowdhury, Z.Z. (2014). Carbon nanotube membranes for water purification: A bright future in water desalination. Desalination, 336, 97-109.

[45] Corry, B. (2008). Designing carbon nanotube membranes for efficient water desalination. Journal of Physical Chemistry B, 112 (5), 1427-1434.
[46] Bakajin, O., Noy, A., Fornasiero, F., Grigoropoulus, C.P., & Holt, J.K., In: J.B., Kim, S., Park, H.G. (2009). Nanofluidic Carbon Nanotube Membranes: Applications for Water Purification and Desalination, in: Savage, et al., (Eds.), Willian Andrew Inc. Elsevier, New York, p. 77-93.
[47] Gehrke, I., Geiser, A., & Somborn-Schulz, A. (2015). Innovations in nanotechnology for water treatment. Nanotechnology, Science and Applications, 8, 1-17
[48] Vatanpour, V., Madaeni, S.S., Moradiane, R., Zinadini, S., & Astinchap B (2012) Novel antibiofouling nanofiltration polyethersulfone membrane fabricated from embedding TiO_2 coated multiwalled carbon nanotubes. Separation Purification Technology, 90, 69-82.
[49] Vatanpour, V., Esmaeili, M., Farahani, M.H.D.A. (2014). Fouling reduction and retention increment of polyethersulfone nanofiltration membranes embedded by amine-functionalized multi-walled carbon nanotubes. Journal of Membrane Science, 466, 70-81.
[50] Sumisha, S., Gangasalam, A., Ismail, A.F., Kumar, D.P., & Shankar, M.V. (2015). Functionalized titanate nanotube-polyetherimide nanocomposite membrane for improved salt rejection under low pressure nanofiltration. RSC Advance, 5, 39464-39473.
[51] Feng. Y., Wang, K., Davies, C.H.J., & Wang, H. (2015). Carbon nanotube/alumina/polyethersulfone hybrid hollow fiber membranes with enhanced mechanical and anti-fouling properties. Nanomaterials, 5, 1366-1378.