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Fabrication of layer-by-layer ion exchange membrane by applying PDA-POSS nanocomposite onto a heterogeneous cationic substrate for water treatment

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Abstract

Double-layer Cation Exchange Membranes (DLCEMs) have been prepared by surface polymerization of dopamine-co-POSS nanoparticles on a PVC-based heterogeneous cation exchange membrane. FTIR and FESEM images proved relatively uniform forming of intended DLCEMs. The FESEM images illustrated almost integrity dispensation of nanoparticles through the surface layer. Results represented that developing a nanocomposite layer resulted in surface hydrophilicity enhancement. The obtained data for Cu^{2+} and Cr^{2+} removal percentage for the prepared membranes represents a higher capacity for DLCEMs to remove heavy metals compared to the pristine cationic membranes. Also, membranes showed higher Cr^{2+} removal capacity rather than Cu^{2+}. The membrane surface modification by introducing PDA nanocomposite also caused to improving sodium permeability and flux. Furthermore, the transport number and permselectivity of the prepared CEMs generally follow an increasing procedure nearly. It should be noticed that the incorporation of POSS nanoparticles into the surface layer resulted in electrical resistance reduction obviously.

Keywords: Electrodialysi, Double layer Membrane, Electrochemical Characterization, Water Treatment

1. Introduction

In recent years Ion Exchange Membranes (IEMs) have been utilized extensively in electrodialysis systems for desalination, industrial effluent treatment possessing heavy metals, food processing and supplying basic chemical products [1-4]. So, many studies have been performed lately and a number of renovation methods have been introduced to membrane-based separation research to achieve separation systems with higher efficiency, sufficient mechanical strength and more cost-effectiveness. In this case, some modification techniques have been proposed to be used such as polymer blending [5,6], incorporating organic/inorganic additives [7, 8], using a vast variety of ionic functional groups [9,10] and utilizing a thin surface modifier [11, 12]. As time is going on, many novel functional ion exchange membranes (IEMs) prepared with nanofillers have illustrated optimistically functional application points of view among all various fields in research studies and also in industries [13, 14]. Most recently Doublelaceratin Exchange Membranes Membranes (DLCEMs) have received ssubstantiallyattraction and have been investigated in manyelectrodialysiss (ED) studies [15]. In ED which is considered as an electrochemical separation process, cation and anion exchange membranes are applied to transfer ions selectively from one compartment to another under an electrochemical potential gradient [16, 17]. Many outstanding advantages of ED compared with Reverse Osmosis (RO) and NanoFiltration (NF) such as high water recovery, thermal, chemical and mechanical stability, acceptable separate properties and also effective behavioural characteristics to remove harmful ions from feed water, may justify widely application of the ED technique for the treatment of more brackish water [18-21]. In spite of some advantages discussed above, fouling of IEMs can be the main difficulty in the ED separation procedure, since the membrane body is usually considered to be a hydrophobic polymer due to the plasticization tendency of hydrophilic one in aqueous environments. Although hydrophobic polymers are likely to adsorb foulants, these materials can be surface modified to improve their hydrophilicity by a few techniques such as plasma treatment [22] or chemical oxidation and grafting [23]. Up to now, a surface modification with polydopamine (PDA) has attracted considerable interest to increase the membrane's antifouling potential [24, 25]. As a matter of fact, in an alkaline aqueous solution, Dopamine can be oxidized and its polymerization may occur to create a crosslinked PDA. PDA is a hydrophilic bio-inspired polymer that can deposit onto any solid surface. Vaselbehagh et al, reported that the antifouling potential can improve with the increase in surface charge density and hydrophilicity in their IEMs coated by PDA [26].

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So far, the surface modification of hydrophobic porous MMMs by adhesive poly(dopamine) has been studied only occasionally.

In the present study, the polymerization of dopamine and different loadings of POSS nanoparticles in the casting solution are investigated to prepare PVC-PDA-DLCEM and PVC-PDA-POSS-DLCEMs. Cage-like structure, organic-inorganic compatibility and different functional and reactive groups of POSS nanoparticles make them act as polymer cross-linkers and improve physicochemical characteristics [27].

2. Experimental

2.1. Materials

Actually, all solvents and reagents were commercially available and applied as received. Polyvinylchloride (PVC, S-7054, density: 490 g/l, viscosity number:105 cm3/g) supplied by BIPC, Bandar Imam, Iran was applied as a polymer binder. Tetrahydrofuran (THF, Mw: 72.11, density: 0.89 g/cm3) was utilized as the solvent. Dopamine hydrochloride was purchased from Sigma-Aldrich. Glutaraldehyde (GA) (25% by weight water- soluble) is provided by Sigma Aldrich. Polyhedraloligomericsilsesquioxane (POSS) nanoparticles was synthesized and used in accordance with previous work as published earlier [28].

2.2. Preparation of surface-modifiedCEMs (PVC-PDA- DLCEMs)

In this study, the cation exchange membranes (CEMs) which were applied as the substrate have been prepared via the casting solution process. To attain this goal, the polymer used as the main body (PVC) was dissolved in THF solvent in a glass reactor with the ratio of (1: 20) (W/V) equipped with a mechanical stirrer model: VelpSientifica Multi 6 stirrer) for more than 5 h. For the next step, grigrounsin particles (ion exchanger Amberlyst1 15, strongly acidic cation exchanger, H^+ form more than 1.7 meq/g dry, density: 0.6 gr/cm3, particle size (0.355–1.18 mm), ≥90% Merck) in a certain amount ((Resin particle: Polymer inder) (w/w), (1:1)) was added to the polymeric solution. Utilizing an ultrasonic instrument (Parsonic, S11, S/N PN-88159, Iran, 28 KHz, and 150W), the mixture was sonicated for 90 min for breaking up the particles aggregates. The obtained solution was then casted on nonwoven fitting fabric and have been left at room temperature (~ 25 °C) to be dried. In this stage, dopamine hydrochloride and different loading ratios of POSS nanoparticles as filler additives were dissolved in 30 ml deionized (DI) water and sonicated for 2h to fabricate the DLCEMs. As represented, the casting solution compositions of prepared membranes were characterized in table 1. The circular pieces of PVC-CEMs were prewetted by deionized (DI) water 1 h, and immediately transferred and immersed into the prepared solution @ pH 10 for dopamine polymerization on the membrane surface. Moreover, a few drops GA as a cross-linking agent was poured into the solution. The reaction continued for 3 hours at 90 °C. ultimately, the obtained surface-modified DLCEMs were rinsed with DI water to remove the alkaline substance on the surface.

Table 1. Prepared CEM samples composition

Membrane Sample number (CEM_x)	Membrane sample	Dopamine (W/W)	POSS (W/W)
CEM_1	PVC-CEM	0.00/100	0.00/100
CEM_2	PVC- PDA-DLCEM	7.00/100	0.00/100
CEM_3	$PVC-PDA-POSS-DLCEM_1$	7.00/100	0.10/100
CEM_4	$PVC-PDA-POSS-DLCEM_2$	7.00/100	0.30/100
CEM_5	$PVC-PDA-POSS-DLCEM_3$	7.00/100	0.70/100

2.3. Characterization

Field Emission Scanning Electron Microscopy (FESEM, Razi-foundation, model MIRA3TESCAN-XMU) was utilized to capture the surface morphology of the prepared CEM. Also to gain more information about the prepared membrane's chemical structure, dried samples were evaluated by a single beam Fourier transform infrared spectrometer (FTIR, Galaxy series 5000) in the range from 4000 to 200 cm^{-1}. Moreover to provide information about surface hydrophilicity or hydrophobicity and photocatalytic effects of the prepared membranes contact angle (CA) was measured by using deionized water at ambient temperature.

2.3.1. Heavy Metal Ions Removal

To investigate the prepared membrane's performance in heavy metal ion removal, an electrodialysis test cell which consists of three parts has been applied. Cu^{2+} and Cr^{2+} cations have been studied in the present work. The middle part of the electrodialysis cell functioned with an aqueous solution of $CuSO_4$ and $CrSO_4$. The treated solution was collected after 30 min for measuring the separation performance of the system and finally analyzed by atomic emission spectroscopy. The residual cations concentration has been utilized to estimate the separation percentage. It should be noted that the pH of the feed was adjusted neutral condition.

2.3.2. Electrochemical measurements

2.3.2.1. Permeability and flux

To measure the ionic flux, two NaCl solution samples (0.1 M/0.01 M) were placed on each side of a test cell (Fig. 1) with platinum electrodes. Across the cell, a DC electrical potential was applied. During the experiment, both parts were stirred energetically to reduce the effects of boundary layers. So the cations can pass through the membrane towards the cathodic section. Ionic flux through the membrane was measured by considering the pH changes in the compartments [30].

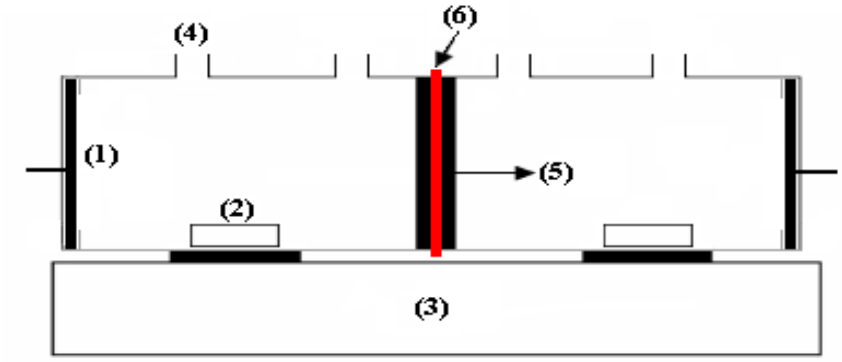

Fig. 1. Schematic diagram of ED test cell: (1) Pt electrode, (2) magnetic bar, (3) stirrer, (4) orifice, (5) rubber ring, (6) membrane.

2.3.2.2. Transport number and permselectivity

The current fraction carried by a special ion is considered as ion transport number, characterized as follows [31,32]:

$$t_i = \frac{Z_i J_i}{\sum_i Z_i J_i} \quad (2)$$

to measure the mean dynamic transport number (MDT) equation 8 can be utilized. The permselectivity has been analyzed based on the counter ions migrations through the membrane and is characterized as below:

$$P_s = \frac{t_i^m - t_0}{1 - t_0} \quad (3)$$

Where t_0 is defined as the transport number of counter ions [32-34].

2.3.3. Electrical resistance

At first, prepared CEMs were incorporated into a cell with an electrolyte solution to reach the first electrical resistance (R_1). The second electrical resistance (R_2) was measured by making use of the apparatus without a membrane. Ultimately, membrane electrical resistance can be specified utilizing the following equations:

$$R_m = R_1 - R_2 \quad (4)$$

$$r = R_m A \quad (5)$$

Where r is a real resistance and A is the CEM surface area.

3. Results and discussion

3.1. Prepared CEMs Characterization

3.1.1. Morphologicalogical study

Fig. 2 displays the FTIR spectra of POSS, pure PVCand PVC-PDA-POSS-DLCEM. The FTIR spectrum was performed to attain a better evaluation of bond formation. Obtained results represented bonds at 3000-3500 cm^{-1} associated with the –OH, -NH groups in prepared DLCEMs due to the presence of polydopamine and functionalize-POSS nanoparticles on the membrane surface. The cage structure of Si-O-Si groups in POSS are clear in the bonds at around 1100 cm^{-1}. Actually, a peak can be seen in the 1493 cm^{-1}, 1600 cm^{-1} and 1250 cm^{-1} which are regarded to aromatic C−C stretching vibrations, N−H bending vibrations, and aromatic amine C−N stretching vibrations, respectively which represents the existence of the aromatic rings in dopamine [35, 36] and also the peak at 1198.17 cm^{-1} is attributed to the partial inter-chain interactions between C–Cl bonds (in PVC) and

C–N bonds (in dopamine) [37]. The CH_2 and CF_2 groups in PVC are recognized clearly in 1330–1429 cm^{-1} and 1096–1250 cm^{-1}, respectively [38,39].

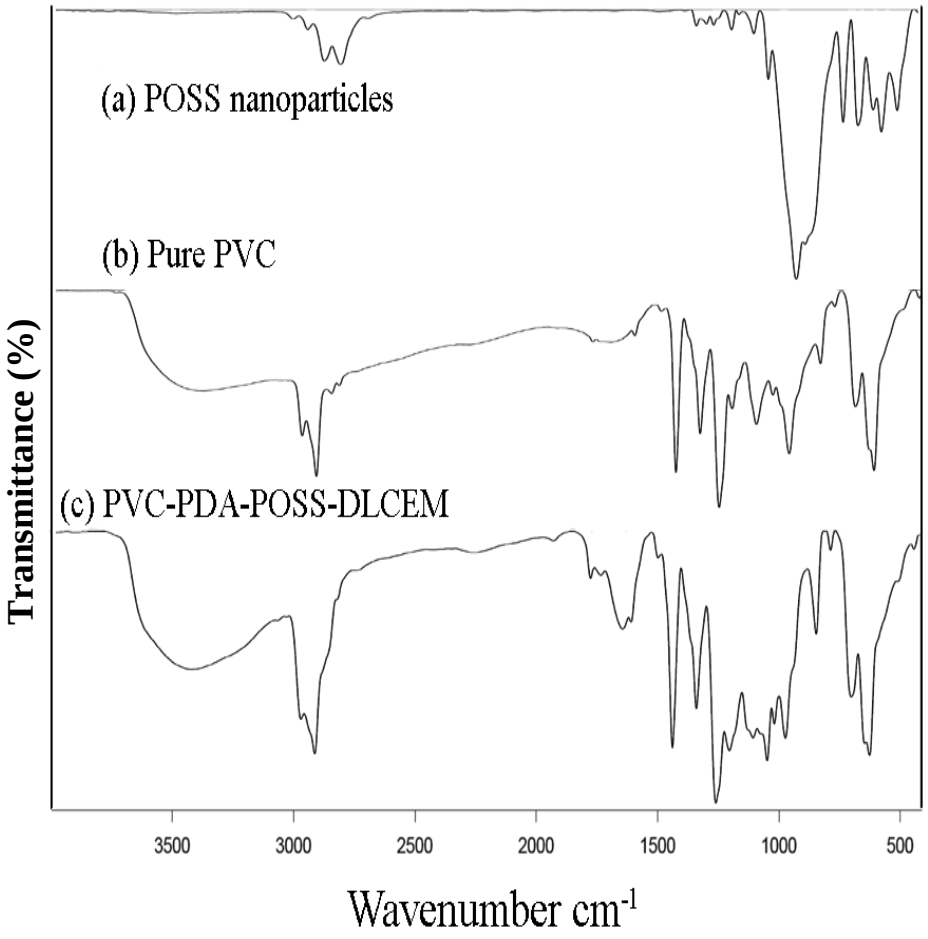

Fig. 2. FTIR spectra of (a) POSS nanoparticles, (b) pure PVC, (c) PVC-PDA-POSS- DLCEM.

Figs. 3 and 4 which indicat FESEM images of prepared CEMs identified nearly structural homogeneity and integrity of studied DLCEMs samples as a result of surface modification with PDA and also the incorporation of POSS as additives. As it can be observed the resin particles and also POSS additives are fairly uniform dispersed on the membrane's surface. With utilizing PDA and also with incorporating nanoparticles into membrane casting solution (Figs. 3b and 4c) which resulted in M_2 and M_3 samples, cavities and voids have been developed due to sudden emersion of additives and finally, with an increase in nanoparticles loading ratio up to 0.7 wt% (M_5), making use of high concentration of POSS additives in membrane structure made more uniformity at a few points and in some cases it can partly progress nanoparticles agglomeration (Fig. 3d).

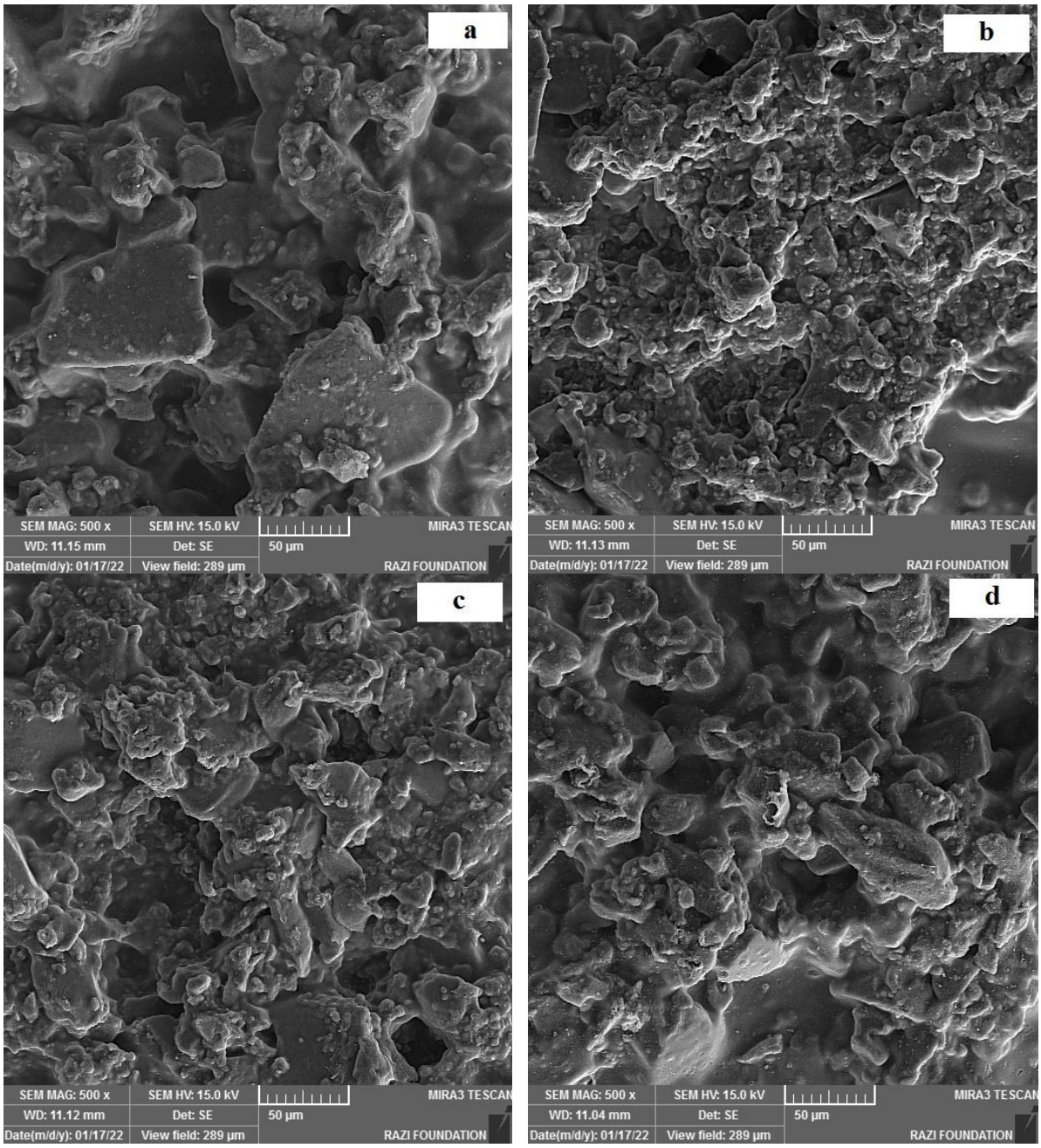

Fig. 3. FESEM images of prepared CEMs samples with a 500x magnification for (a) CEM_1 (b) CEM_2 (c) CEM_3 and (d) CEM_5.

As illustrated in Fig. 4 the roughness of the membrane surface has been increased partly with membrane surface modification with dopamine (Fig. 4b), although in many studies suitable antifouling potential and also more hydrophilicity characteristics of PDA have been proved. Also, it is recognized that rough surfaces may represent lower antifouling properties rather than smooth ones [40].

So, it is worth mentioning here that the most optimal loading ratio of dopamine has been considered in this study via the competition between the antifouling potential improvement resulting from the increase in membrane surface hydrophilicity and the decrease in antifouling potential due to the increase in membrane surface roughness.

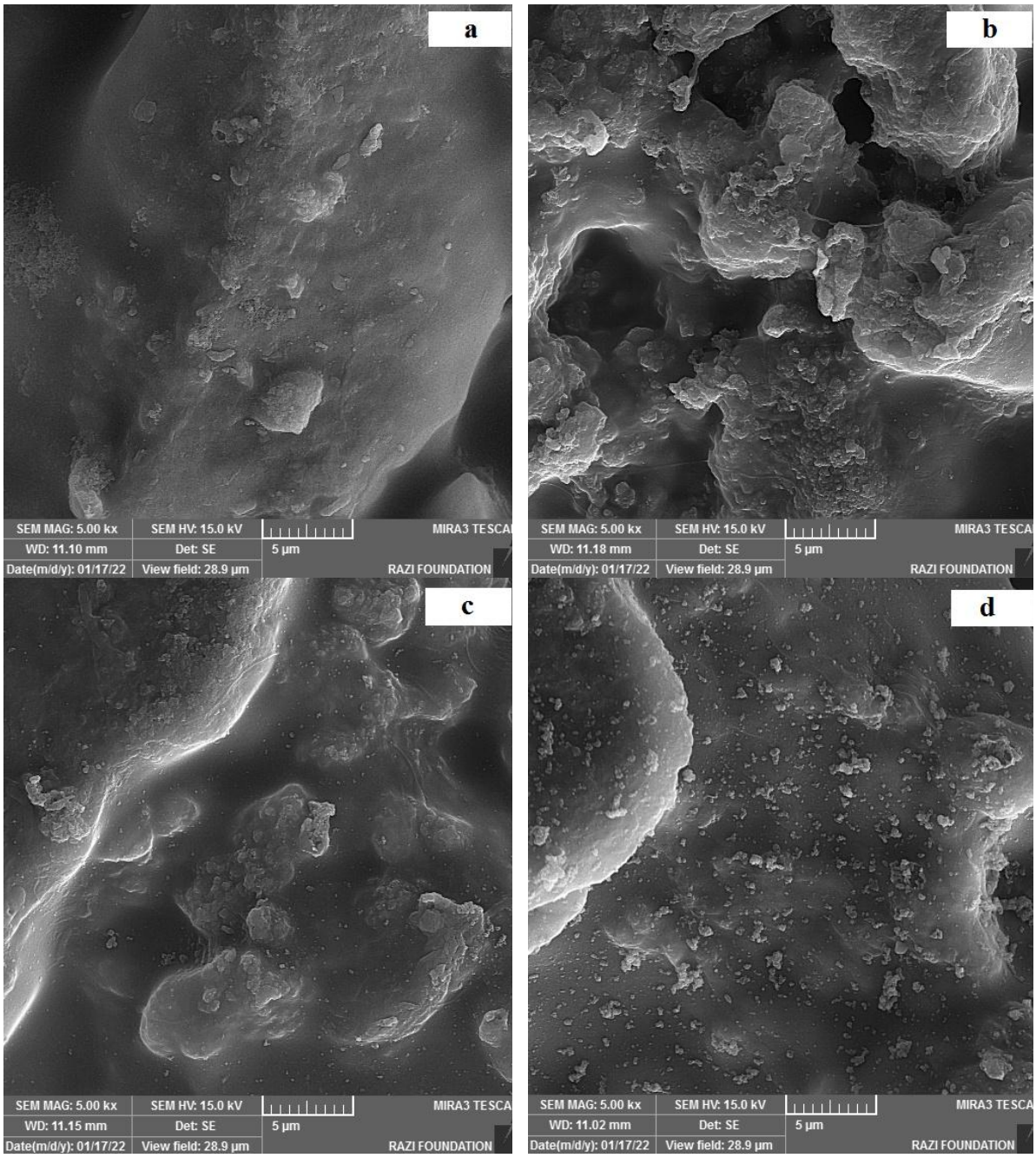

Fig. 4. FESEM image of prepared CEMs samples with a 5000x magnification for (a) CEM_1 (b) CEM_2 (c) CEM_3 and (d) CEM_5.

3.1.2. Water uptake

Fig. 5 obviously illustrates water content percentage improvement by the incorporation of both PDA and POSS into the membrane structure. higher hydrophilic nature of PDA and also utilizing POSS nanoparticles in membrane casting solution have resulted in a clear enhancement trend that can cover the hydrophobicity nature of the substrate membrane surface [26]. Also, it can be derived that the heterogeneity increasing of the membrane structure and developing cavities and voids which has been regarded as the sudden appearance of POSS nanoparticles, should have been effective in representing such behaviour as indicated in figure 3. As can be seen in figure 5, with a further increase in POSS nanoparticles up to 0.7 wt%, the water uptake amount in the prepared CEMs has still been representing a rising manner. This situation may mean that with an increase in the loading ratios of POSS particles in the membrane matrix, higher uniformity and spreading and lower agglomeration of nanoparticles can be expected as it is clear in Fig. 4d [41].

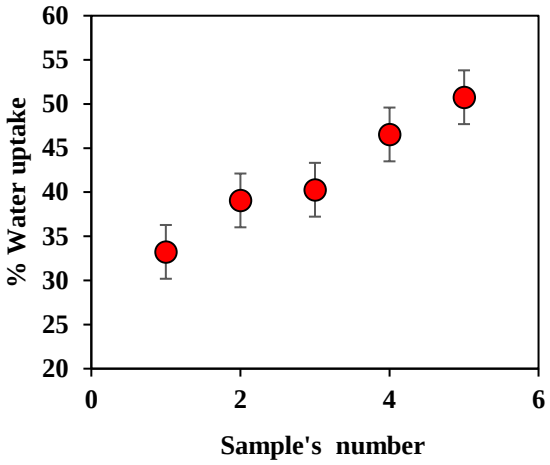

Fig. 5. water uptake of prepared CEMs.

3.1.3. Metal ion removal

The obtained data for Cu^{2+} and Cr^{2+} removal rateS of prepared membranes are illustrated in Table 2. The improved behaviour for modified membranes can be attributed to higher water content and better hydrophilicity characteristic of PDA resulting from the presence of –NH and –OH groups, more adsorptive sites and also higher porosity of prepared CEMs (created by POSS incorporation into the membrane matrix) that all enhance the removal rate for the heavy metal ion. Also, the electrostatic exclusion of ions produced by the negative charges on the membrane surface can be considered as a justification for higher heavy metal removal [42,43]. Furthermore, it should be mentioned that with more increase in POSS loading ratio up to 0.3 wt% in membrane casting solution, the CEMs samples removal capacity of Cu^{2+} and Cr^{2+} experiences a decreasing trend as it is clear in Table 2. This certain type of behaviour can be related to the agglomeration of the nanoparticles which may lead to lower porosity and also lower adsorption sites [44, 45]. Moreover, higher valence ions represent more repulsion from the membrane surface. The ion removal increases by increasing the valence of co-ion.Since the heavy metal removal improves with an increase in hydrated radius and charge of anions, Generally, a high hydrated radius and lower ionic radius lead to lower diffusion of ions into the nanofibers and membrane surface. As a matter of fact, the ion removal capacity improves with an increase in the valence of co-ion and hydrated radius because of more repulsion of ions with higher valence. Also, a high hydrated radius alongside with lower ionic radius leads to lower diffusion of ions into the nanoparticles and membrane surface. Therefore, Cr^{2+} with a higher hydrated radius and lower ionic radius than Cu^{2+} has displayed higher removal capacity than Cu^{2+} which can be caused by the steric hindrance effects and the ions tough pass across nanoparticles [42, 46].

Table 2. The Cu^{2+} and Cr^{2+} removal rate for prepared membranes

Membrane (M_x)	Membrane sample	Cu^{2+} removal rate	Cr^{2+} removal rate
M_1	PVC-CEM	17.04	27.46
M_2	PVC- PDA-DLCEM	23.43	30.82
M_3	$PVC-PDA-POSS-DLCEM_1$	25.09	28.29
M_4	$PVC-PDA-POSS-DLCEM_2$	14.61	11.83
M_5	$PVC-PDA-POSS-DLCEM_3$	16.98	23.71

3.1.4. Desalination measurement

3.1.4.1. Permeability and flux

Changing procedures of flux and permeability for prepared CEMs are displayed in Fig. 6. Membrane surface modification with PDA may enhance both ionic permeability and flux which can be attributed to the hydrophilicity properties of PDA and controlled interspaces between accumulated PDA and nano aggregates [31]. On the other hand, a suitable amount of water uptake, and also the ionic pathways formation in the prepared membrane structure may have resulted in both permeability and flux enhancement due to an increase in POSS loading ratio in the casting solution up to 0.1 wt%. However, with further increase in nanoparticles concentration from 0.1 to 0.7 wt%, the ionic permeability and flux generally began a decreasing manner. This particular type of action may be regarded as narrow channel formation which can control ions passing through the membrane matrix and exactly for the studied DLCEMs can restrict the ion transportation as it is clear in figure 6. Also, nanoparticle agglomeration at some points with more concentration of POSS in the casting solution which helps to decrease membrane charge density, can be considered as a justification for this decreasing behaviour [47].

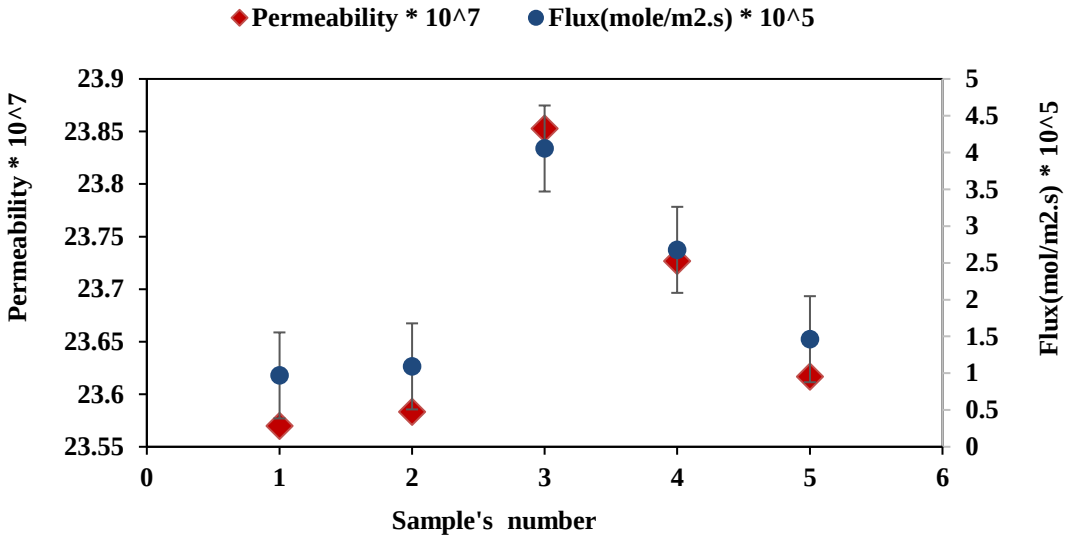

Fig. 6. Sodium permeability and flux for prepared CEMs.

3.1.4.2. The permselectivity

The perm-selectivity of the prepared membranes is indicated in Table 3. It can be concluded that the results totally represented an increasing or constant procedure except for M_4. This improvement can be recognized more clearly by utilizing PDA as a surface modifier and also at higher concentrations of POSS nanoparticles up to 0.7 wt%. This is attributed to the adsorption properties of PDA due to the presence of –NH and –OH groups and more adsorptive sites of nanoparticles which cause to increase in surface charge density and membrane potential [47]. On the other hand, the pore filling in the prepared CEMs restricts the channels used to pass the ions and creates a compact membrane structure, with improved Donnan exclusion. Ultimately the controlling procedure of the ionic agent groups and resin particles can overcome ion passing which may cause increases in transport number and permselectivity. It should be noticed that the nearly considerably lower amount of transport number and perm selectivity for M_4 compared to other prepared CEMs can be justified with water content enhancement which may decrease the transport number and permselectivity. In such similar situations, higher amounts of water content may facilitate ion passing through the channels [29].

Table 3. The permselectivity for the prepared membranes

Membrane Sample (M_x)	Permselectivity
M_1	>94±7
M_2	>89±6
M_3	>88±5
M_4	>80±8
M_5	>83±7

3.1.5. Electrical resistance (ER)

Table 4 indicates the areal electrical resistance of the studied CEMs samples. As it is significantly obvious in the figure, membrane surface modification with PDA has to increase in the areal electrical resistance. Incorporation of POSS in to membrane casting solutionhas been resulted in ER reduction (M_3). In this condition, possibility of ion transportation may increase and because of that membrane electrical resistance may decrease. With more increase in POSS nanoparticles concentration in the membrane structure up to 0.7 wt%, membrane electrical resistance increases clearly in comparison with unmodified membrane sample which can be regarded as restriction of the ions transportation through the membrane matrix. It can be concluded that voids may be surrounded more by nanoparticles and as a result, ionic pathways decrease [47]. Therefore in a similar situation, ER increases with more increase in nanoparticles concentration in the modifier layer.

Table 4. The real electrical resistance of prepared CEMs: unmodified and modified membranes

Membrane Sample (M_x)	Resistance ($\Omega.cm^2$)
M_1	17.78±3.5
M_2	23.45±4.1
M_3	19.14±3.6
M_4	20.20±2.8
M_5	21.89±3.1

4. Conclusion

It was found that the surface hydrophilicity of the prepared CEMs was increased in the appearance of PDA alongside with incorporation of POSS nanoparticles. Novel DLCEMs can represent higher sodium flux in comparison with unmodified membrane. Also, modified membranes showed appropriate water content, higher permeability and flux and more reasonable permselectivity. In some cases, surface modified membrane with PDA and incorporation of POSS nanoparticleadditives can improve the removal ability of heavy metal ion from water. In general, PVC-PDA-DLCEMs in A lower loading ratios of POSS nanoparticles are more functional in desalination and heavy metal removal.

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References

[1] K. Venugopal, S. Dharmalingam, Desalination efficiency of a novel bipolar membrane based on functionalized polysulfone, Desalination, 296 (2012) 37–45. https://doi.org/10.1016/j.desal.2012.04.006.
[2] A. H. Galama, N. A. Hoog, D. R. Yntema, Method for determining ion exchange membrane resistance for electrodialysis systems. Desalination, 380 (2016) 1–11. https://doi.org/10.1016/j.desal.2015.11.018.
[3] F. QayoomMir, A. Shukla, Sharp decline in counter-ion transport number of electrodialysis ion exchange membrane on moderate increase in temperature. Desalination, 372 (2015) 1–6. https://doi.org/10.1016/j.desal.2015.06.009.
[4] S. M. Hosseini, E. Jashni, S. Amani, B. Van der Bruggen, Tailoring the electrochemical properties of ED ion exchange membranes based on the synergism of TiO_2 nanoparticles-co-GO nanoplates. J. Colloid Interface Sci., 505 (2017)763–775. https://doi.org/10.1016/j.jcis.2017.06.045.
[5] M. Reig, H. Farrokhzad, B. Van der Bruggen, O. Gibert, Cortina JL Synthesis of a monovalent selective cation exchange membrane to concentrate reverse osmosis brines by electrodialysis. Desalination, 375 (2015) 1–9.https://doi.org/10.1016/j.desal.2015.07.023.
[6] H. Farrokhzad, S. Darvishmanesh, G. Genduso, T. Van Gerven, B. Vander Bruggen, Development of bivalent cation selective ionexchange membranes by varying molecular weight of polyaniline. Electrochim. Acta 158 (2015) 64–72. https://doi.org/10.1016/j.electacta.2015.01.062.
[7] J. Li, X. Wang, G. Zhao, C. Chen, Z. Chai, A. Alsaedi, T. Hayat, X. Wang, Metal–organic framework-based materials: superior adsorbents for the capture of toxic and radioactive metal ions. Chem. Soc. Rev. 47 (2018) 2322–2356. https://doi.org/10.1039/C7CS00543A.
[8] S. M. Hosseini, P. Koranian, P. Gholami, S. S. Madaeni, A. R. Moghadassi, A. R. Khodabakhshi, Fabrication of mixed matrix heterogeneous ion exchange membrane by multiwalled carbon nano-tubes: electrochemical characterization and transport properties of mono and bivalent cations. Desalination, 329 (2013) 62–67. https://doi.org/10.1016/j.desal.2013.09.007.
[9] R. K. Nagarale, G. S. Gohil, V. K. Shahi, R. Rangarajan, Preparation and electrochemical characterizations of cation exchange membranes with different functional groups. Colloids Surf. A Physicochem Eng. Asp., 251 (2004) 133–140. https://doi.org/10.1016/j.colsurfa.2004.09.028.
[10] S. M. Hosseini, S. Rafiei, A. R. Hamidi, A. R. Moghadassi, S. S. Madaeni, Preparation and electrochemical characterization of mixed matrix heterogeneous cat filled with zeolite nanoparticles: ionic transport property in desalination. Desalination, 351 (2014) 138–144. https://doi.org/10.1016/j.desal.2014.07.036.

[11] A. R. Moghadassi, P. Koranian, S. M. Hosseini, M. Askari, S. S. Madaeni, Surface modification of heterogeneous cation exchange membrane through simultaneous using polymerization of PAA and multi walled carbon nanotubes, J. Ind. Eng. Chem., 30 (2014) 2710–2718. https://doi.org/10.1016/j.jiec.2013.10.059.
[12] A. N. Rojas, Y. O. Maldonado, L. M. T. Rodriguez, An easy methode to modify the exchange membranes of electrodialysis withelectro synthesized polyaniline. J. Membr. Sci., 300 (2007)2–5. https://doi.org/10.1016/j.memsci.2007.05.013.
[13] S. M. Hosseini, S. S. Madaeni, A. R. Khodabakhshi, Preparation and characterization of heterogeneous cation exchange membranes based on S-polyvinylchloride and polycarbonate. Sep. Sci. Technol., 46 (2011) 794–808 https://doi.org/ 10.1080/01496395.2010.534122.
[14] V. Vatanpour, S. S. Madaeni, A. R. Khataee, E. Salehi, S. Zinadini, H. Ahmadi Monfared, TiO_2 embedded mixed matrix PES nanocomposite membranes: influence of different sizes and types of nanoparticles on antifouling and performance, Desalination, 292 (2012) 19–29. https://doi.org/10.1016/j.desal.2012.02.006.
[15] T. Xu, Ion exchange membrane: state of their development and perspective. J. Membr. Sci. 263 (2005) 1–29. https://doi.org/10.1016/j.memsci.2005.05.002.
[16] H. Strathmann, Electrodialysis, a mature technology with a multitude of new applications, Desalination, 264 (2010) 268–288. https://doi.org/10.1016/j.desal.2010.04.069.
[17] F. J. Borges, H. Roux-de Balmann, R. Guardani, Investigation of themass transfer processes during the desalination of water containing phenol and sodium chloride by electrodialysis. J. Membr. Sci. 325 (2008) 130–138. https://doi.org/10.1016/j.memsci.2008.07.017.
[18] M. Tahaikt, I. Achary, M.A. Menkouchi Sahli, Z. Amor, M. Taky, A. Alami, A. Boughriba, M. Hafsi, A. Elmidaoui, Defluoridation of Moroccan groundwater by electrodialysis: continuous operation. Desalination, 189 (2006) 215–220. https://doi.org/10.1016/j.desal.2005.06.027.
[19] L. J. Banasiak, A.I. Schäfer, Removal of boron, fluoride and nitrate by electrodialysis in the presence of organic matter, J. Membr. Sci. 334 (2009) 101–109. https://doi.org/10.1016/j.memsci.2009.02.020.
[20] K. Kesore, F. Janowski, V. A. Shaposhnik, Highly effective electrodialysis for selective elimination of nitrate from drinking water. J. Membr. Sci. 127 (1997) 17–24. https://doi.org/10.1016/S0376-7388(96)00282-7.
[21] M. A. Menkouchi Sahli, S. Annouar, M. Tahaikt, M. Mountadar, A. Soufiane, A. Elmidaoui, Fluoride removal for underground brackish water by adsorption on the natural chitosan and by electrodialysis. Desalination, 212 (2007) 37–45. https://doi.org/10.1016/j.desal.2006.09.018.
[22] K. S. Kim, K. H. Lee, K. Cho, C. E. Park, Surface modification of polysulfonultrafiltration membrane by oxygen plasma treatment. J. Membr. Sci., 19 (2002) 135–145. https://doi.org/10.1016/S0376-7388(01)00686-X.
[23] M. Ulbricht, H. Matuschewski, A. Oechel, H.-G. Hicke, Photo-induced graft polymerization surface modifications for the preparation of hydrophilic and low-proten-adsorbing ultrafiltration membranes, J. Membr. Sci., 115 (1996) 31–47. https://doi.org/10.1016/0376-7388(95)00264-2.
[24] J.-H. Jiang, L.-P. Zhu, X.-L. Li, Y.-Y. Xu, B.-K. Zhu, Surface modification of PE porous membranes based on the strong adhesion of polydopamine and covalent immobilization of heparin. J. Membr. Sci., 364 (2010) 194–202. https://doi.org/10.1016/j.memsci.2010.08.017.
[25] S. Kasemset, A. Lee, D. J. Miller, B. D. Freeman, M. M. Sharma, Effect of polydopamine deposition conditions on fouling resistance, physical properties, and permeation properties of reverse osmosis membranes in oil/water separation. J. Membr. Sci., 425-426 (2013) 208–216. https://doi.org/10.1016/j.memsci.2012.08.049.
[26] M. Vaselbehagh, H. Karkhanechi, S. Mulyati, R. Takagi, H. Matsuyama, Improved antifouling of anion-exchange membrane by polydopamine coating in electrodialysis process. Desalination, 332 (2014) 126–133. https://doi.org/ 10.1016/j.desal.2013.10.031.
[27] X. You, H. Wu, Y. Su, J. Yuan, R. Zhang, Q. Yu, M. Wu, Z. Jiang, X. Caod, Precise nanopore tuning for high-throughput desalination membrane via codepostion of dopamine and multifunctional POSS. J. Mater. Chem. A., 27 (2018) 1-330. https://doi.org/10.1039/C8TA03673J.
[28] S. Bandehali, F. Parvizian, A. Moghadassi, S. M. Hosseini, High water permeable PEI nanofiltration membrane modified by L-cysteine functionalized POSS nanoparticles with promoted antifouling/separation performance. Sep. Purif. Technol., 237 (2020) 116361. https://doi.org/10.1016/j.seppur.2019.116361.
[29] M. Nemati, S. M. Hosseini, F. Parvizian1, N. Rafiei, B. Van der Bruggen, Desalination and heavy metal ion removal from water by new ion exchange membrane modified by synthesized $NiFe_2O_4$/HAMPS nanocomposite. Ionics, 25 (2019) 3847-3857. https://doi.org/10.1007/s11581-019-02937-2.
[30] S. M. Hosseini, A. Seidypoor, M. Nemati, S. S. Madaeni, F. Parvizian, E. Salehi, Mixed matrix heterogeneous cation exchange membrane filledwith clay nanoparticles:membranes' fabrication and characterization in desalination process, J. Water Reuse Desalination, 6 (2016) 290-300. https://doi.org/10.2166/wrd.2015.064.
[31] H. Strathmann, Membrane science and technology series: ion-exchange membrane separation processes. vol 9. Elsevier, Netherlands, 2004.
[32] R. Nagarale, V. K. Shahi, S. Thampy, R. Rangarajan, Studies on electrochemical characterization of polycarbonate and polysulfone based heterogeneous cation-ex-change membranes. React. Funct. Polym., 61 (2004) 131–138. https://doi.org/10.1016/j.reactfunctpolym.2004.04.007.

[33] R. J. Hunter, Calculation of activity coefficient from Debye-Huckel theory. J. Chem. Educ., 43 (1966) 550–554. https://doi.org/10.1021/ed043p550.
[34] S. Bandehali, A. Moghadassi, F. Parvizian, Y. Zhang, S. Mohsen Hosseini, J. Shen, New mixed matrix PEI nanofiltration membrane decorated by glycidyl-POSS functionalized graphene oxide nanoplates with enhanced separation and antifouling behaviour: heavy metal ions removal. Sep. Purif. Technol., (2020) 116745. https://doi.org/10.1016/j.seppur.2020.116745.
[35] Y. Xie, L. Yue, Y. Zheng, L. Zhao, C. Liang, W. He, Z. Liu, Y. Sun, Y. Yang, The antibacterial stability of poly (dopamine) in-situ reduction and chelation nano-Ag based on bacterial cellulose network template, Appl. Surf. Sci., 491 (2019) 383-394. https://doi.org/10.1016/j.apsusc.2019.06.096.
[36] S. Bandehali, F. Parvizian, A.R. Moghadassi, S.M. Hosseini, Copper and lead ions removal from water by new PEI based NF membrane modified by functionalized POSS nanoparticles. J. Polym. Res., 26 (2019) 211-219. https://doi.org/10.1007/s10965-019-1865-7.
[37] A. Seidypoor, E. Joudaki, S.M. Hosseini, S. Bandehali, Double-layer electrodialysis cation exchange membrane by introducing chitosan/TiO_2 thin-film nanocomposite on PVC-based substrate for Cu removal from water. Ionics, 28 (2022) 3037–3048. https://doi.org/10.1007/s11581-022-04518-2.
[38] S. Bandehali, A. Moghadassi, F. Parvizian, J. Shen, S. Hosseini, Glycidyl POSS-functionalized ZnO nanoparticles incorporated polyether-imide based nanofiltration membranes for heavy metal ions removal from water. Korean J. Chem. Eng., 37 (2020) 263-273. https://doi.org/s11814-019-0441-5.
[39] J. Liu, X. Shen, Y. Zhao, L. Chen, Acryloylmorpholine-grafted PVDF membrane with improved protein fouling resistance, Ind. Eng. Chem. Res., 52 (2013) 18392-18400. https://doi.org/10.1021/ie403456n.
[40] E. M. Vrijenhoek, S. Hong, M. Elimelech, Influence of membrane surface properties on initial rate of colloidal fouling of reverse osmosis and nanofiltration membranes. J. Membr. Sci., 188 (2001) 115–128. https://doi.org/ 10.1016/S0376-7388(01)00376-3.
[41] S. Bandehali, F. Parvizian, A.R. Moghadassi, S.M. Hosseini, J.N. Shen, Fabrication of thin film-PEI nanofiltration membrane with promoted separation performances: Cr, Pb and Cu ions removal from water. J. Polym. Res., 27 (2020) 94. https://doi.org/10.1007/s10965-020-02056-x.
[42] S. Bandehali, A. Moghadassi, F. Parvizian, S. Hosseini, A new type of [PEI-glycidyl POSS] nanofiltration membrane with enhanced separation and antifouling performance. Korean J. Chem. Eng., 36 (2019) 1657-1668. https://doi.org/10.1007/s11814-019-0359-y.
[43] S. Bandehali, , F. Parvizian, S. M. Hosseini, T. Matsuura, E. Drioli, J. Shen, A. Moghadassi, A. S. Adeleye, Planning of smart gating membranes for water treatment. Chemosphere., 283 (2021) 131207. https://doi.org/10.1016/j.chemosphere.2021.131207.
[44] S. M. Hosseini, M. Afshari, A. R. Fazlali, S. Koudzari Farahani, S. Bandehali, B. Van der Bruggen, E. Bagheripour, Mixed matrix PES-based nanofiltration membrane decorated by (Fe_3O_4–polyvinylpyrrolidone) composite nanoparticles with intensified antifouling and separation characteristics. Chem. Eng. Res. Des., 147 (2019) 390-398. https://doi.org/10.1016/j.cherd.2019.05.025.
[45] S. Bandehali, , F. Parvizian, A. Moghadassi, S. M. Hosseini. Nanomaterials for the efficient abatement of wastewater contaminants by means of reverse osmosis and nanofiltration. In nanomaterials for the detection and removal of wastewater pollutants, pp. 111-144. Elsevier, 2020. https://doi.org/10.1016/B978-0-12-818489-9.00005-0.
[46] S. M. Hossein, M. Aliabadi Farahani, H. Khalili, B.Van der Bruggen, M. Nemati, Z. Rajabi, A. Ahmadi, $CuFe_2O_4$ magnetic nanoparticles to improve the ionic transfer properties ofelectrodialysis heterogeneous cation exchange membrane. Ionic, 25, (2019) 725-1734. https://doi.org/10.52547/CNJ.1.1.51.