2024年臺灣國際科學展覽會
優勝作品專輯

作品編號　030033

參展科別　化學

作品名稱　Development of a nano-filtration membrane using different linear aliphatic amines and linear cross-linkers for purification of expensive and precious organic solvents

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1. Background information:

The separation, purification, and recovery of precious organic solvents is a huge challenge for many industries including petroleum and pharmaceutical companies, since these companies use huge quantities of organic solvents [1-2]. Natural dissolvable nanofiltration(ON)has atremendous potential for supplanting a few energy-concentrated crude purging techniques, similar to refining and extraction[3- 4 - 5]. The importance of OSN is obvious from the fact that one cubic meter of methanol requires 1750 MJ of energy for distillation since the process of distillation is comprised of heating, evaporation, and condensation while OSN can purify the same volume of methanol by consuming 3 MJ of energy [6-7]. Additionally, OSN is a useful technology since it is simpler to use than conventional purification and separation methods. The membrane's pore structure, which influences both its selectivity and permeance, has a significant impact on how well the membranes perform [8-9]. In general, the trade-off between flux and selectivity affects the membrane's performance. As a result, the membranes' flux and permeability are affected by the tailoring and tuning of their pore structure. Therefore, designing an efficient nanofiltration membranes with ideal porosity is highly desirable.

Interfacial polymerization (IP) is highly versatile as it provides a freedom of selection of various monomers for targeting a specific application such as nanofiltration and reverse osmosis The potential for organic solvent nanofiltration (ON) to replace various energy-intensive traditional purification techniques, such as distillation and extraction, is enormous. [8-9]. Despite the fact that many different monomers have been successfully used by utilizing IP to create thin film composite nanofiltration TFC-NF membranes, one of the main limitations of such membranes continues to be the poor selection of closely related comparable nanometer sized solutes. Many efforts are still being made to develop potential monomers with the perfect properties for creating membranes that operate excellently [10-11]. Another strategy is also getting more popular in which different porous additives are added to the TFC membrane either at the support level or active layer level. These additives include carbon organic frameworks (COFs), metal organic frameworks (MOFs), hyper-cross-linked porous polymers (HCPs), and natural polymers such as chitosan [12-13-14-15]. However, maintaining the crystallinity of such additives, particularly MOFs that lead to crystalline membranes, is extremely difficult while other additions suffer from aggregation and agglomeration that results in membrane flaws that impair the performance of the membranes [16]. Therefore, changing the chemistry of the reacting monomer during IP can significantly alter the structure of the resultant active layers of the membranes.

The current study was carried out by using linear aliphatic amines 4A-3P and 4A on a crosslinked PAN support. The study was carried out through interfacial polymerization between either 4A-3P and TPC or 4A and TPC on crosslinked PAN. In comparison to the previous studies where cyclic amines such as piperazine or aromatic amines such as meta-phenylenediamine (MPD) are used, we have used linear aliphatic amines 4A and 4A-3P crosslinked with organic phase containing terephthaloyl chloride (TPC) as a cross-linker. The IP reaction was carried out between amine and TPC on a crosslinked PAN support. The fabricated membrane was extensively characterized by using scanning electron microscope (SEM), ATR-FTIR, water contact angle (WCA), energy dispersive X-ray (EDX) and elemental mapping . The fabricated membrane was used for OSN applications by using dead-end filtration setup.

2. Problem of study

The preparation of efficient OSN nanofiltration membrane is essential for recovering precious organic solvents. The traditional OSN membrane fabrication are fabricated by using cyclic [Piperazine; PIP] or aromatic diamines [meta-phenylenediamine; MPD]. These diamines have only two reaction sites which limits the degree of crosslinking. The current project is aimed at increasing the number of reaction sites per amine molecule and hence the aliphatic tetra-amines (4A and 4A-3P) will be used during IP.

3. Questions of study

- Does using aliphatic linear amines would yield OSN membrane with good separation potential?
- Does linear cross-linker TPC would lead to sufficient cross-linking in active layer?
- How the OSN membrane performance varies with changing aliphatic amine?

4. Aims and objectives

Major aim: The main aim of the proposal is to use different aliphatic linear amines for fabrication of efficient OSN membrane

Specific aims:

- To carry out crosslinking of PAN using hydrazine
- To do IP on crosslinked PAN support with cross-linker solution to develop hyper-cross-linked polyamide active layer
- To carry out extensive characterization of the fabricated membrane through scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analysis, Water contact angle (WCA), Fourier transform infra-red spectroscopy (FTIR) and UV visible spectrophotometry.

- To test the fabricated membrane for OSN performance study
- To optimize the parameters for membrane filtration performance

5. Hypothesis

Since petroleum and pharmaceutical firms utilize enormous amounts of organic solvents, the separation, purification, and recovery of precious organic solvents is a significant challenge for many industries. The potential for organic solvent nanofiltration (ON) to replace various energy-intensive traditional purification techniques, such as distillation and extraction, is enormous. The aim of this research is to design and fabricate a thin film composite nanofiltration membrane by using Interfacial polymerization process. In order to target a particular application, such as nanofiltration and reverse osmosis, interfacial polymerization (IP) offers the opportunity to choose from a variety of monomers [10-17]. The active layer of the membrane can be tuned by using IP where different amines and cross-linkers can be used for polyamide active layer. The aromatic diamines MPD and PIP offer two reaction sites which will be replaced by more reaction sites per molecule leading to nanofiltration membranes. This research focuses on using linear aliphatic amines (4A and 4A-3P) and linear cross-linker TPC to design hyper-cross linked thin film composite OSN membranes.

6. Variables

Dependent variables: The flux (LMH; L $m^{-2}h^{-1}$) of the different solvents through the membrane

Independent variables: The applied transmembrane pressure (bar)

7. Importance of study

The current study is extremely important as it would open up a new era of using aliphatic amines for fabricating efficient OSN membranes. The OSN membranes will be an exceptional choice for recovering and purifying highly precious organic solvents. Moreover, the OSN membranes can also be used purifying an active pharmaceutical ingredient (API) in pharmaceutical companies. The OSN membrane are highly cost effective and less energy intensive.

8. Materials and Methods

8.1 Materials

Terephthaloyl chloride (TPC), N,N′-Bis(2-aminoethyl)-1,3-propanediamine (4A-3P Amine), N,N'-bis(3-aminopropyl)ethylenediamine (4A), triethylamine (TEA), polyacrylonitrile (PAN), n-hexane, N,N'-dimethyl formamide (DMF), polyester terephthalate (PET) fabric, methylene blue (MB), eriochrome black T (EBT), Congo red (CR) were all purchased from Sigma Aldrich (St. Louis, USA). Deionised (DI) water from in-lab setup was used for all the experiments.

8.2 Fabrication of membranes

8.2.1 *Fabrication of PAN and crosslinking of PAN*

The PAN dope solution was prepared by dissolving 12 g of perfectly dried PAN in 88 g of DMF. The solution was stirred at room temperature overnight leading to a transparent solution of PAN. The PAN dope solution was allowed to stand until all of the air bubbles were completely removed. The PAN support was prepared by spreading an appropriate amount of PAN dope solution on a PET sheet affixed on a glass plate. Then the PAN was casted by using a custom made Doctor's blade (100 µm slit width) on PET support. Immediately after casting PAN, the support was dipped in deionized water bath and allowed to stand leading to phase inversion. Hence, PAN/PET ultrafiltration support was fabricated. The PAN support was crosslinked by dipping an appropriate piece PAN/PET support in 25% (v/v) hydrazine (NH_2-NH_2) aqueous solution at 70 ^oC for 8h. Then the crosslinked PAN support was thoroughly washed with an excess of DI water.

8.2.2 *Fabrication of membranes through interfacial polymerization*

The membranes were fabricated through IP reaction on crosslinked PAN support. The crosslinked PAN support was dipped in an aqueous solution of either 4A-3P or 4A amine for 10 minutes with continuous shaking on a seesaw shaker. The amine impregnated crosslinked PAN support was taken out of the aqueous amine solution and excess amine was removed by using a rubber roller. Then amine impregnated crosslinked PAN support was dipped in 0.15% (w/v) n-hexane solution of TPC for 60 s. Then the membrane was removed from TPC solution and washed with fresh n-hexane to remove unreacted TPC from membrane surface. Various steps adopted during fabrication of both membranes are given in the following figure 1.

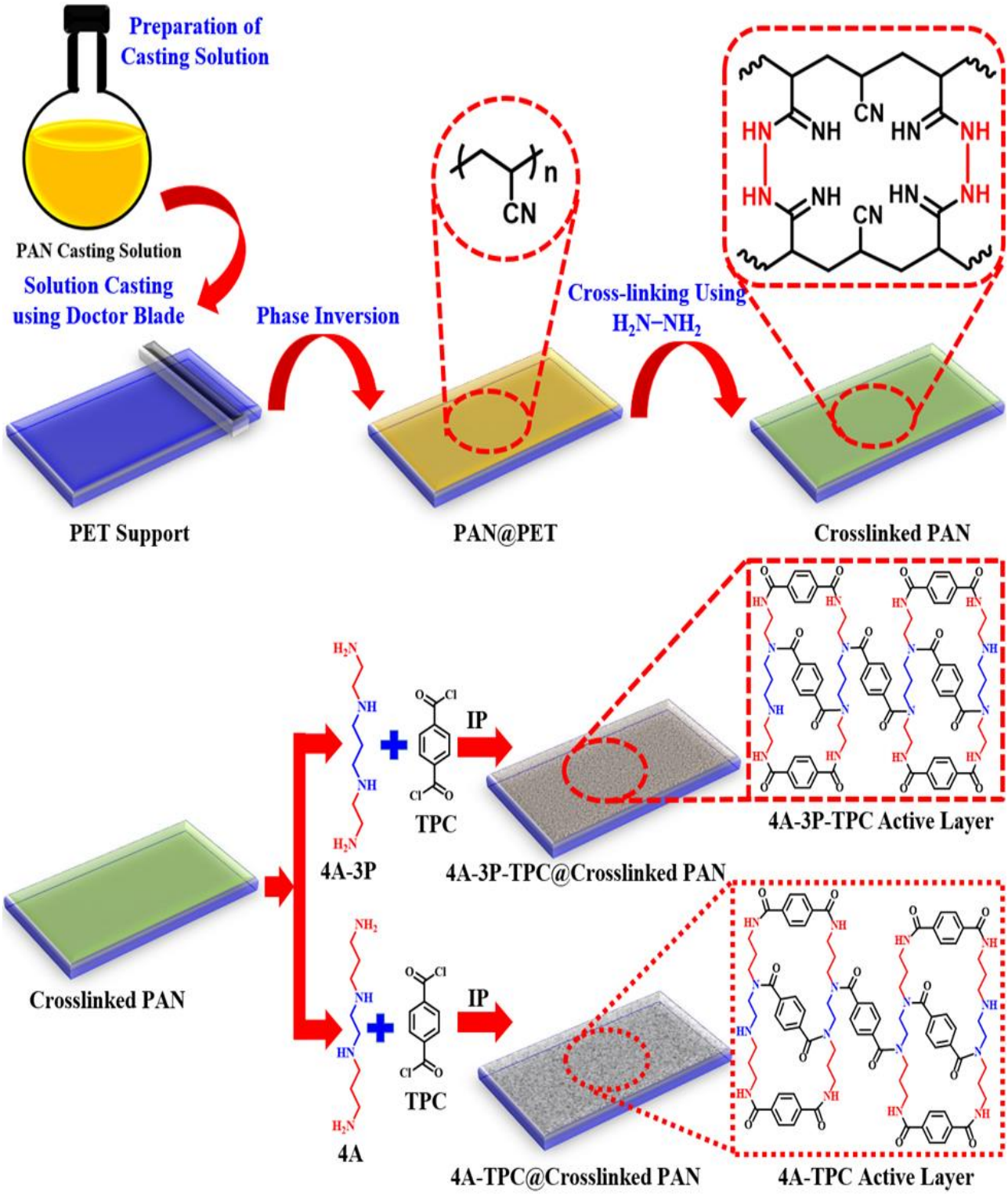


Figure 1. Different stages of fabrication of crosslinked PAN, 4A-TPC@crosslinked PAN and 4A-3P-TPC@crosslinked PAN membrane.

9. Result and discussion

9.1 Characterization of membranes

In order to establish and understand the structure of the different membranes namely crosslinked PAN, 4A-TPC@crosslinked PAN and 4A-3P-TPC@crosslinked PAN. ATR-FTIR of all of the membranes is given in following Figure 2. All of the anticipated fucntional groups have been identified in different membranes. Since all of the FTIR spectra of different membranes contain a broad peak in a range of 3600 cm^{-1} to 3200 cm^{-1} which can be attributed to stretching vibration of N-H bond of amide linkage (-CO-NH) of polyamide active layer of 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN. Similarly, in case of crosslinked PAN, the 3600 cm^{-1} to 3200 cm^{-1} broad peak can be attributed to the existance of –N-H bond generated during croslinking using hydrazine (NH_2-NH_2) as a crosslinking agnet. As we move further, there is a short but relaatively sharp peak located at 2900 cm^{-1}- 2800 cm^{-1} in all of the FTIR spectra of all membranes including crosslinked PAN. This characteristic peak is due to –C-H streching of aliphatic bakbones of polyamide active layer due to constituent amines 4A, 4A-3P and PAN support. Furthermore, a very sharp and deep peak was visible at around 2200 cm^{-1} which is due to residual nitrile (−C≡N) groups of PAN. A relatively medium peak of crosslinked PAN can be seen in the region of 1700 cm^{-1} – 1650 cm^{-1} which can be atributed to the streching vibration of C=C/C=N bonds originated during crosslinking event of PAN with hydrazine. However, in case of 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes, a doublet peak is shown in the region of 1700 cm^{-1} to 1600 cm^{-1}. In addition to C=C/C=N bonds of PAN, 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes have carbonyl fucntional group (>C=O) of the primary/secondary amide linkages of polyamide active layers. The doublet in the region of 1700 cm^{-1} to 1600 cm^{-1} is attributed to C=C/C=N and >C=O bonds of PAN and polyamide active layers. Therefore, the ATR-FTIR spectra of crosslinked PAN, 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes have confirmed the prsence of all the functional groups and bonds in their structure (scheme 1).

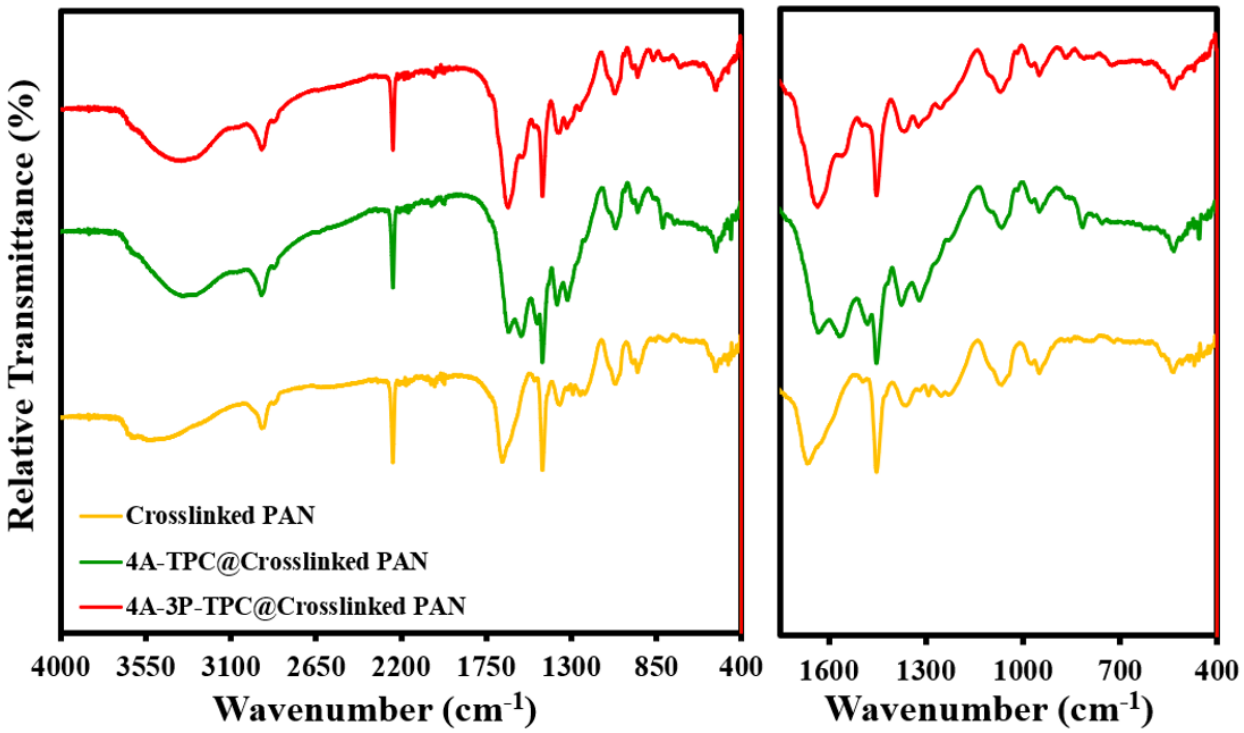


Figure 2. ATR-FTIR spectra of crosslinked PAN, 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes

The membrane's surface morphology was investigated by studying and analysing the SEM micrographs of the crosslinked PAN support, 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes. The crosslinked PAN support appeared highly porous with uniform sponge like structure (Fig0 3a to 3c). After IP, the membrane surface appeared considerably rough owing to the growth of polyamide active layer on support. In case of 4A-TPC@Crosslinked PAN, the polyamide active layer appeared beaded with the beads embedded in the matrix of polaymide. The geometry of 4A-TPC@Crosslinked PAN membrane is resembles ridge and valley structure. However, the ridge and valley conformation is not perfectly adopted by 4A-TPC@Crosslinked PAN membrane as the valleys are filled with polyamide ntework (Fig0 3d to 3f). In case of 4A-3P-TPC@Crosslinked PAN membrane, the polyamide active layer perfectly matches the traditional ridge and valley configuration of polyamide membranes (Fig0 3g to 3i). The variation in the pattern of growth of polyamide active layer on support can be attributed to the change in structure of tetra-amine reacting during IP with the same crosslinker TMC. In case of 4A-3P, secondary amine (-NH-) groups are located at the ends of propyl chain (3C atoms apart) while in case of 4A, the secondary amine (-NH-) groups are separated by ethyl chain (2C atoms apart). The longer chain length provides certain degree of freedom for penetration of TPC leading to

extensive croslinking resulting into the formation of special ridge and valley pattern as in case of 4A-3P amine. In case of 4A, the amine groups are comparatively close together offering less chance for TPC to penetrate. Hnece, the 4A-3P-TPC@Crosslinked PAN membrane possesses a perfect geometry for efficient transfer of solvent molecules while rejecting the solutes as confirmed by filtration experiments. Therefore, the chamistry of the reacting monomers of utmost importance in tuning the performance of the nanofiltration membranes.

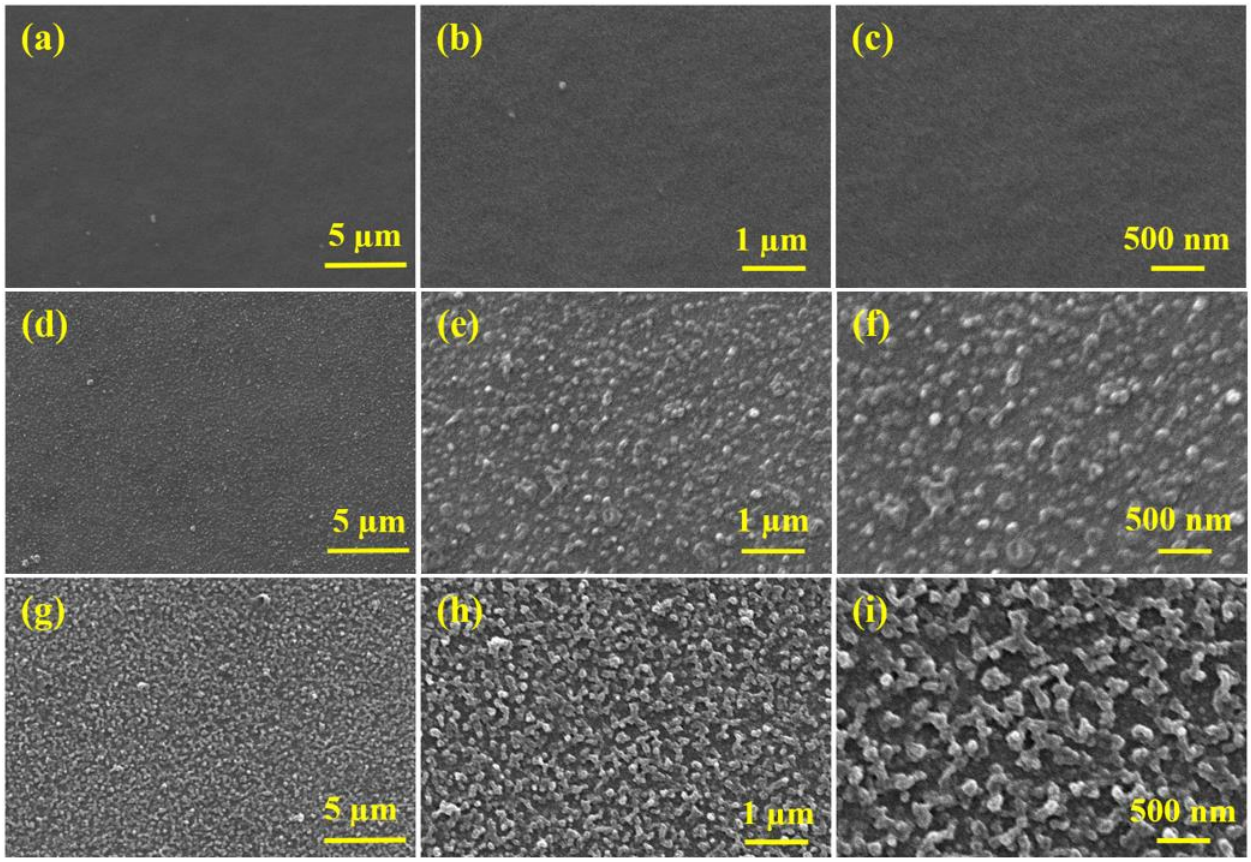


Figure 3. The SEM micrographs of (a - c) Crosslinked PAN support, (d - f) 4A-TPC@Crosslinked PAN membrane and (g - h) 4A-3P-TPC@Crosslinked PAN membrane at diiferent magnifications.

The elemental composition of support, 4A-TPC@Crosslinked PAN membrane and 4A-3P-TPC@Crosslinked PAN membrane was estimated by energy dispersive X-ray (EDX) analysis as shown in Figure 4. The EDX analysis of a selected area showed the presence of all of the elements that were present in contributing amines, TPC, PAN and Hydrazine used during membrane fabrication.

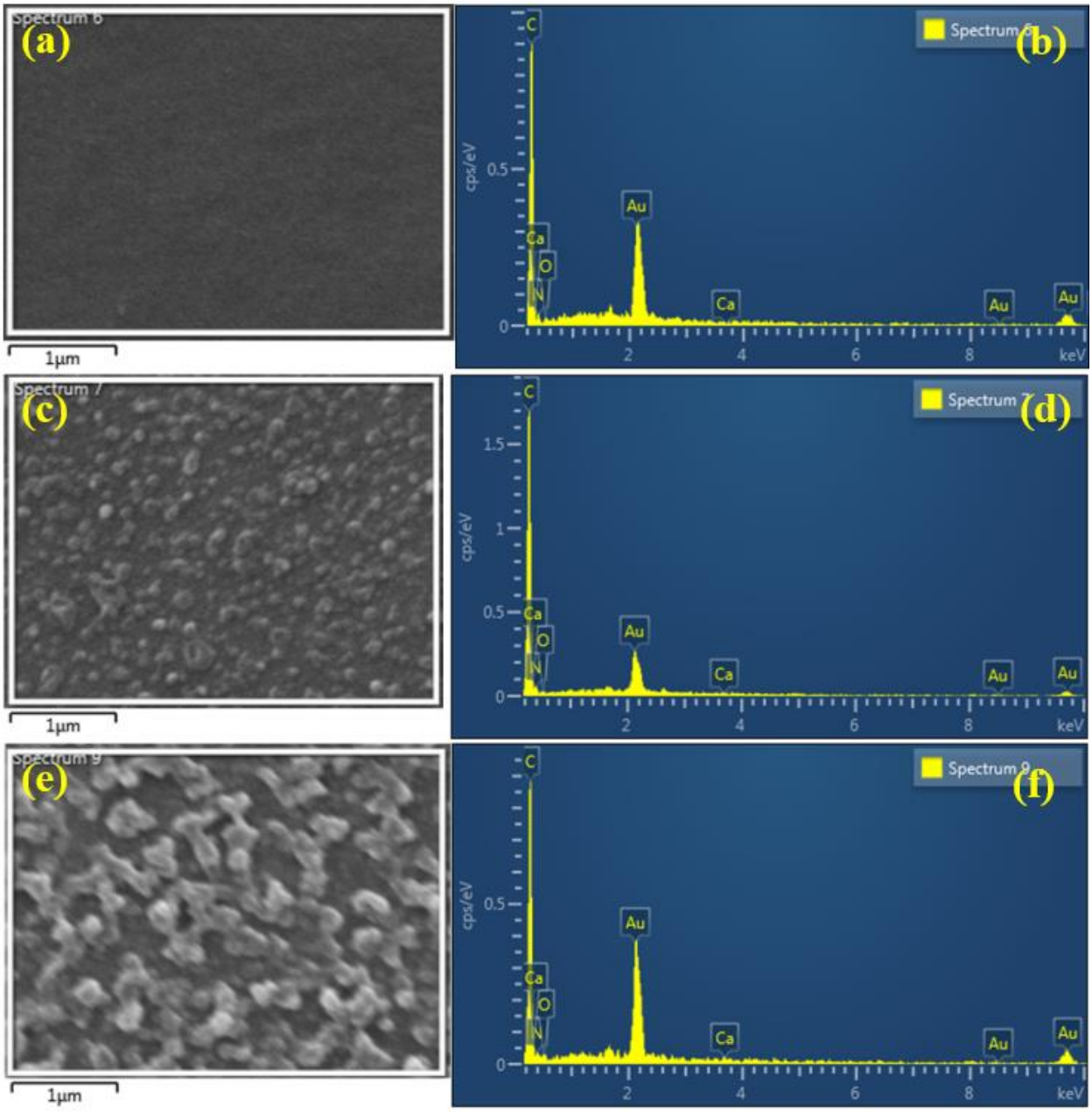


Figure 4. EDX analysis of (a - b) Crosslinked PAN support, (c - d) 4A-TPC@Crosslinked PAN membrane and (e - f) 4A-3P-TPC@Crosslinked PAN membrane.

The elemental mapping analysis revealed a uniform distribution of all of the elements were equally and uniformly distributed throughout the entire membrane (Fig. 5).

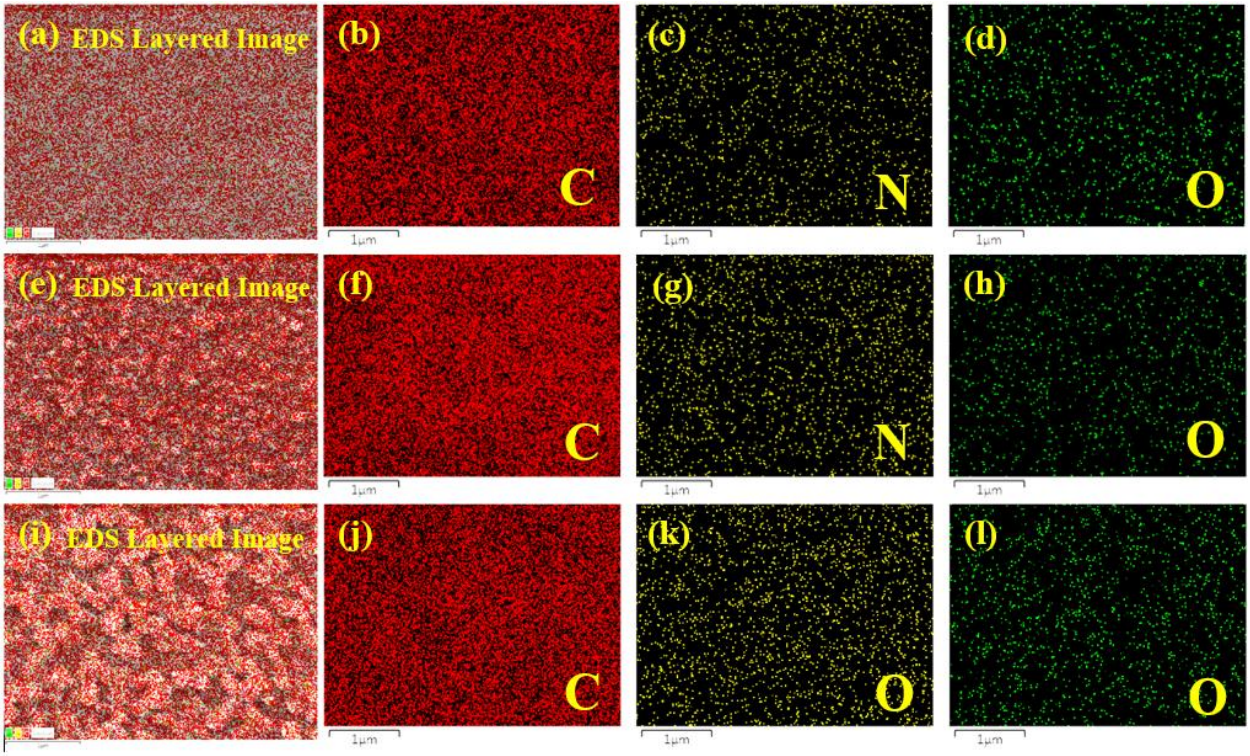
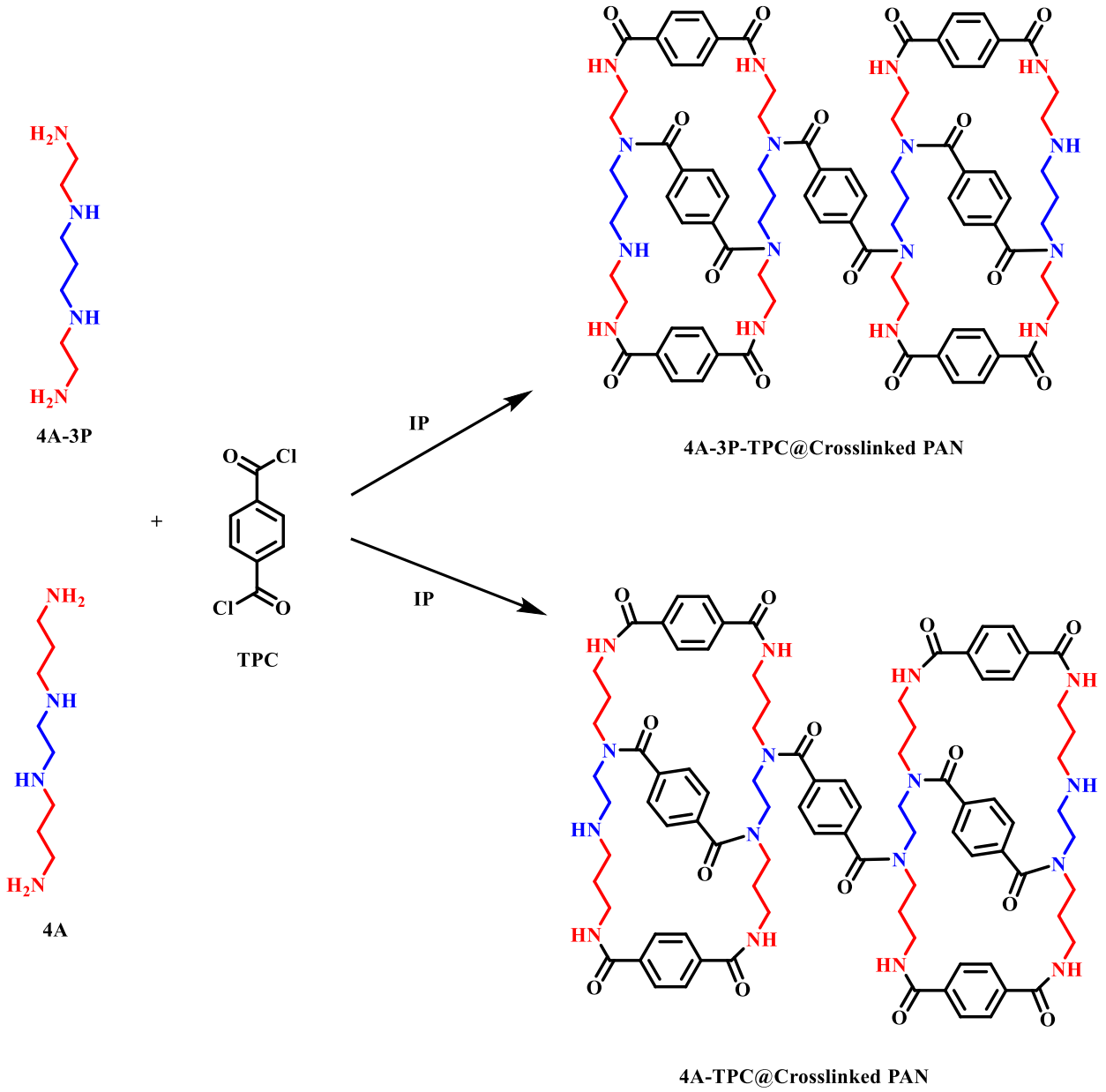


Figure 5. Elemental mapping of (a - d) Crosslinked PAN support, (e - h) 4A-TPC@Crosslinked PAN membrane and (i - l) 4A-3P-TPC@Crosslinked PAN membrane.

The proposed structure of active layers of the fabricated membranes are given below in the following scheme 1. The polyamide active layers are generated as a result of reaction between tetra-amines (4A and 4A-3P) and terephthaloyl chloride (TPC). The 4A and 4A-3P amines have closely resembling structure with difference in the position of amino groups in the structure of tetra-amines. In case of 4A-3P amine, the two secondary amino groups (-NH-) are separated by propyl chain while the primary amino groups (-NH_2) are ethyl chains. This particular structure of 4A-3P allows flexibility of binding of TPC with the neighbouring 4A-3P chains. However, in case of 4A amine, the secondary amino groups (-NH-) are separated by ethyl chains and primary amino groups (-NH_2) are separated by propyl chains. As the secondary amino groups are close together the incorporation of TPC in between is not flexible and uniform (scheme 1). Therefore, the 4A-3P amine leads to the formation of a network with more uniform crosslinking in polyamid active layers. The SEM analysis (Fig. 2g to 2i) confirmed the growth of more extensive crosslinking in polyamide active layer of the membrane.



Scheme 1: Proposed structure of active layers of 4A-TPC@Crosslinked PAN 4A-3P-TPC@Crosslinked PAN

The surface hydrophilicity of the support and fabricated membranes was determined by recording water contact angles (WCAs). It was observed that WCA of the Hydrazine Crosslinked PAN was found to be 45.9^{o} and hence crosslinked PAN support was considerably hydrophilic. The hydrophilicity of crosslinked PAN support can be attributed to contribution of hydrazine introducing amino groups in the support. Furthermore, the hydrophilicity of crosslinked PAN can also be due to partial hydrolysis of the PAN support. However, after the growth of polyamide active layer on crosslinked PAN support, the membrane

surface hydrophilicity was decreased as the WCA was increased (65.1°) in case of 4A-TPC@Crosslinked PAN membrane while 59.9° for 4A-3P-TPC@Crosslinked PAN (Fig. 6). This might be attributed to the covering of highly hydrophilic crosslinked PAN support. In addition, the inclusion of phenyl rings of TPC in polyamide active layer can also contribute to increase the value of WCA lowering the surface hydrophilicity of the membrane. Although, the WCAs of 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes were slightly increased the values of WCAs are still considerably below 90°. Hence, both 4A-TPC@Crosslinked PAN and 4A-3P-TPC@Crosslinked PAN membranes are still quite hydrophilic.

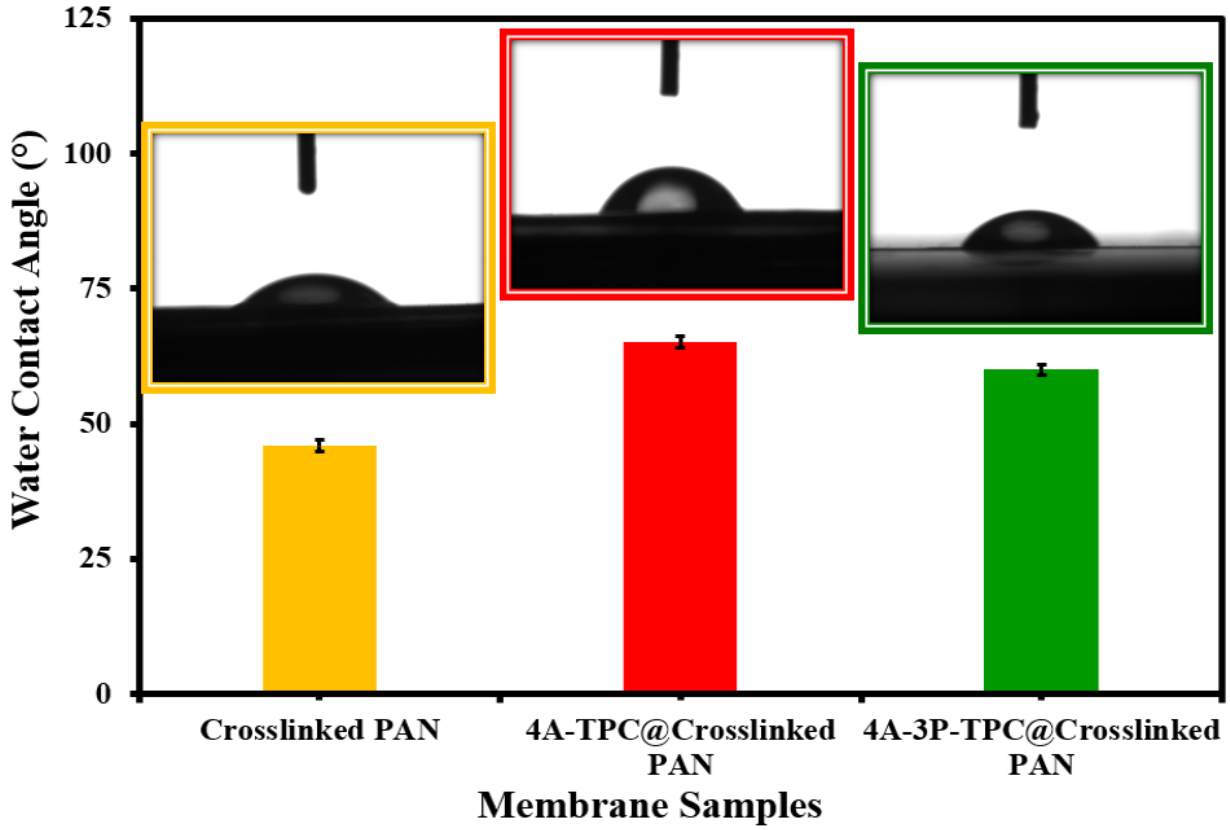


Figure 6. The water contact angles (WCAs) of Crosslinked PAN support, 4A-TPC@Crosslinked PAN membrane and 4A-3P-TPC@Crosslinked PAN membrane.

Another salient feature of membranes is the surface roughness which was measured by recording atomic force microscopy (AFM) images of the crosslinked PAN, 4A-TPC@Crosslinked PAN membrane and 4A-3P-TPC@Crosslinked PAN membrane. The membrane average roughness (R_a) was found to increase in the following order crosslinked PAN > 4A-TPC@Crosslinked PAN membrane > 4A-3P-TPC@Crosslinked PAN membrane (Fig.7).

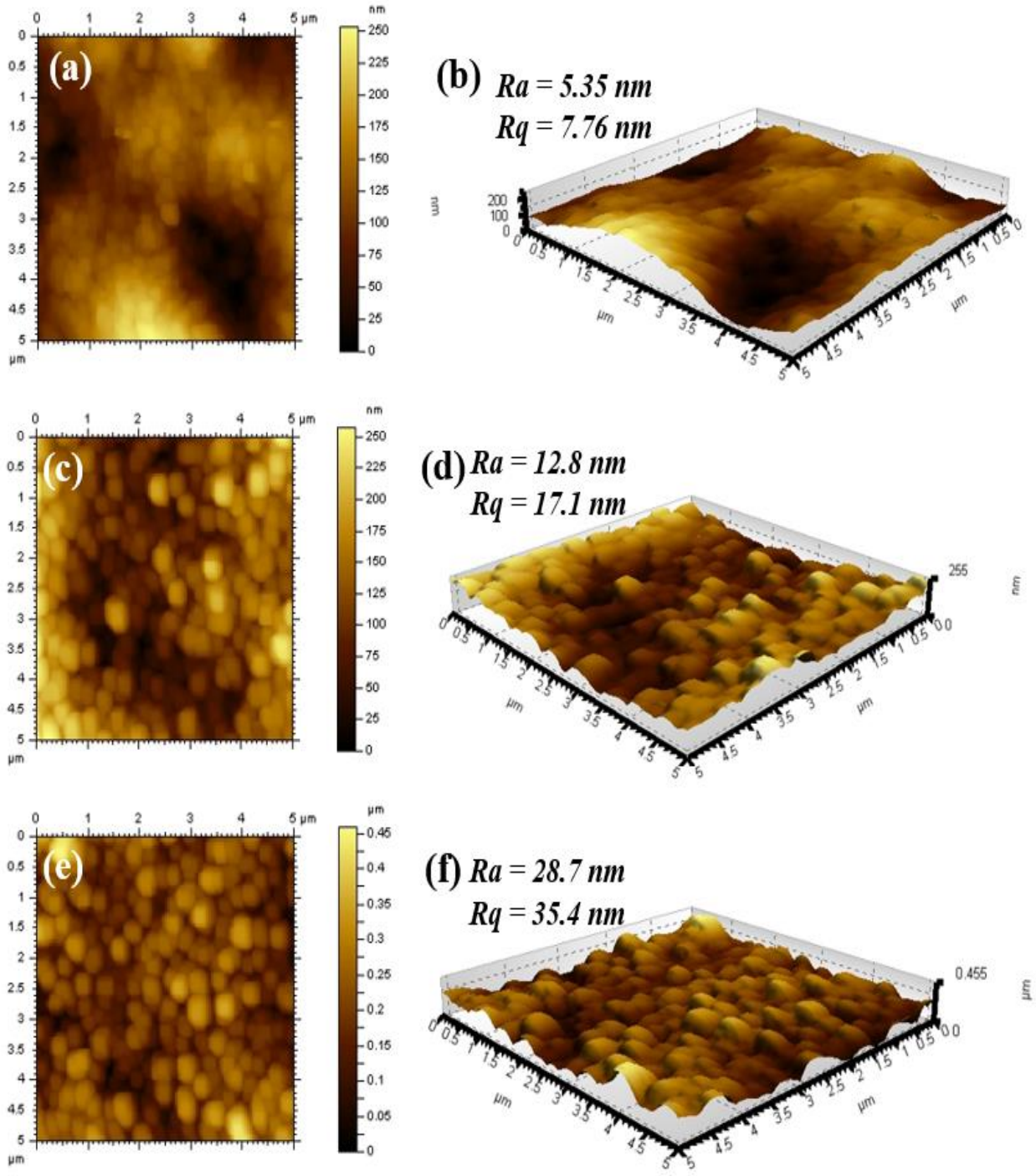


Figure 7. AFM images of (a - b) Crosslinked PAN support, (c - d) 4A-TPC@Crosslinked PAN membrane and (e - f) 4A-3P-TPC@Crosslinked PAN membrane.

9.2 OSN performance of the membranes

Following through characteriation of the membranes, the OSN performance of the membranes was studied by using different polar and non-polar solvents including methanol, ethanol, isopropanol, n-hexane and toluene as feed in dead end filtration cell. The effect of increasing transmembrane pressure on permeate flux was studied as given in Figure 8. The flux was found to be dependant upon transmembrane pressure as the permeate flux of all of the tested solvents increased with increasing transmembrane pressure. The permeate flux of n-hexane and toluene was found to be highest among the tested solvents. In case of 4A-TPC@Crosslinked PAN membrane, the permeate flux of n-hexane and toluene was raised from 33.8 LMH to 81.1 LMH at the pressure was increased from 4 bar to 10 bar (Fig. 8a). Similar findings were also found for 4A-3P-TPC@Crosslinked PAN membrane. However, the permeate flux of all of the solvents was found to be higher compared to 4A-TPC@Crosslinked PAN membrane (Fig. 8b). The n-hexane and toluene showed a flux of 109.9 LMH and 95.5 LMH respectively. This might be attributed to the existance of permissible channels for passage of solvents through the 4A-3P-TPC@Crosslinked PAN membrane due to flexibility for crossliking during IP.

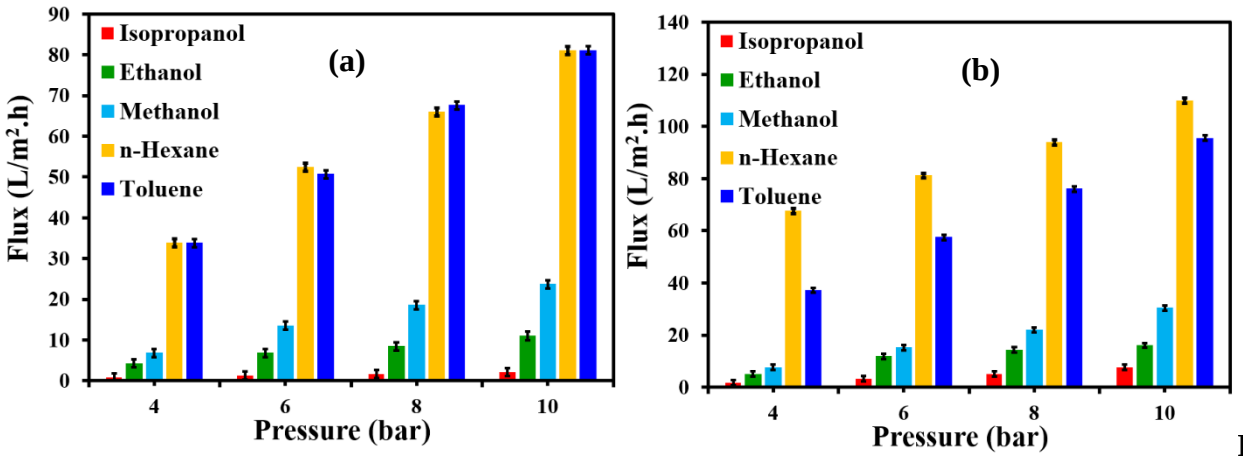


Figure 8. Variation of permeate flux as a function of applied feed pressure using (a) 4A-TPC@Crosslinked PAN and (b) 4A-3P-TPC@Crosslinked PAN membrane

The separation potential of OSN membranes was also studied by using different dyes such as CR, EBT and MB as model solutes. The solution of each dye was prepared by dissolving an approperiate amount of the dye in methanol at a concentration of 10 ppm. The feed of each dye was loaded in the dead end cell and filtration was carried out 4 bar. The flux of both membrane remained constant for all of the tested dyes (Fig. 9a and 9b). During filtration experiments, the permeate flux of clean methanol was found to

be 4.2 LMH for 4A-TPC@Crosslinked PAN membrane while 5.9 LMH for 4A-3P-TPC@Crosslinked PAN membrane (Fig. 9a). The rejection performance of the membranes was analysed by recording the absorption spectrum of the permeates collected during filtration experiments and the rejection data is given in Figure 9b. The CR showed highest rejection reaching to 99.1% for 4A-TPC@Crosslinked PAN membrane and 98.8% for 4A-3P-TPC@Crosslinked PAN membrane. In case of EBT, the rejection stayed at 99.1% for 4A-TPC@Crosslinked PAN membrane while it was slightly reduced for 4A-3P-TPC@Crosslinked PAN membrane reaching to 94.4%. Therefore, the 4A-3P-TPC@Crosslinked PAN membrane proved advantageous comapred to 4A-TPC@Crosslinked PAN membrane as it has comparatively higher permeate flux with comaparable rejection of the solutes. Hence, a slight variation in the structure of the reacting monomers during IP alters the performance of the membrane during filtration experiemnts. The rejection of MB remained considerably lower compared to CR and EBT with 4.4% for 4A-3P-TPC@Crosslinked PAN membrane and 11.1% 4A-TPC@Crosslinked PAN membrane.

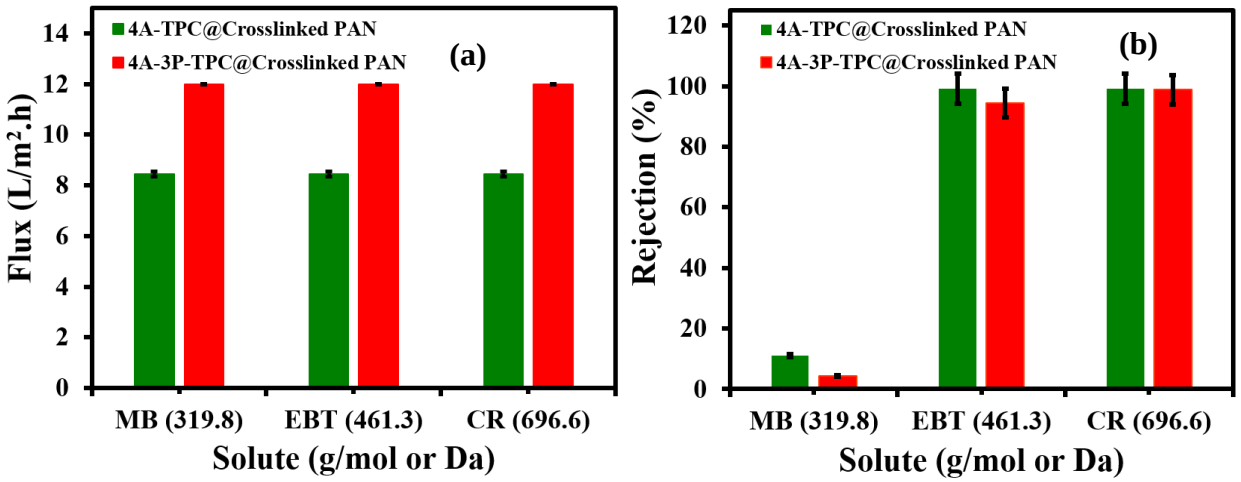


Figure 9. (a) Variation of permeate flux as a function of molecular weight of solutes (dyes) and (b) rejection performance of the 4A-TPC@Crosslinked PAN and (b) 4A-3P-TPC@Crosslinked PAN membrane for different dyes.

The following Figure 10 shows the photographs along with absorption spectrum of the experimental samples of feeds and permeates of CR, EBT and MB. It is clearly evident from the following figure for both membranes that absorption maximum of CR at 500 nm was completely flattened in case of permeates which is also reflected by the colorful solution of CR in methanol and colorless solution of permeates. Similarly, the absorption maximum of EBT at 550 nm was also flattened out in case of permeates for both membranes. However, in case of MB there was not a detectable difference in the absorption spectra and coloration of the feed and permeate samples.

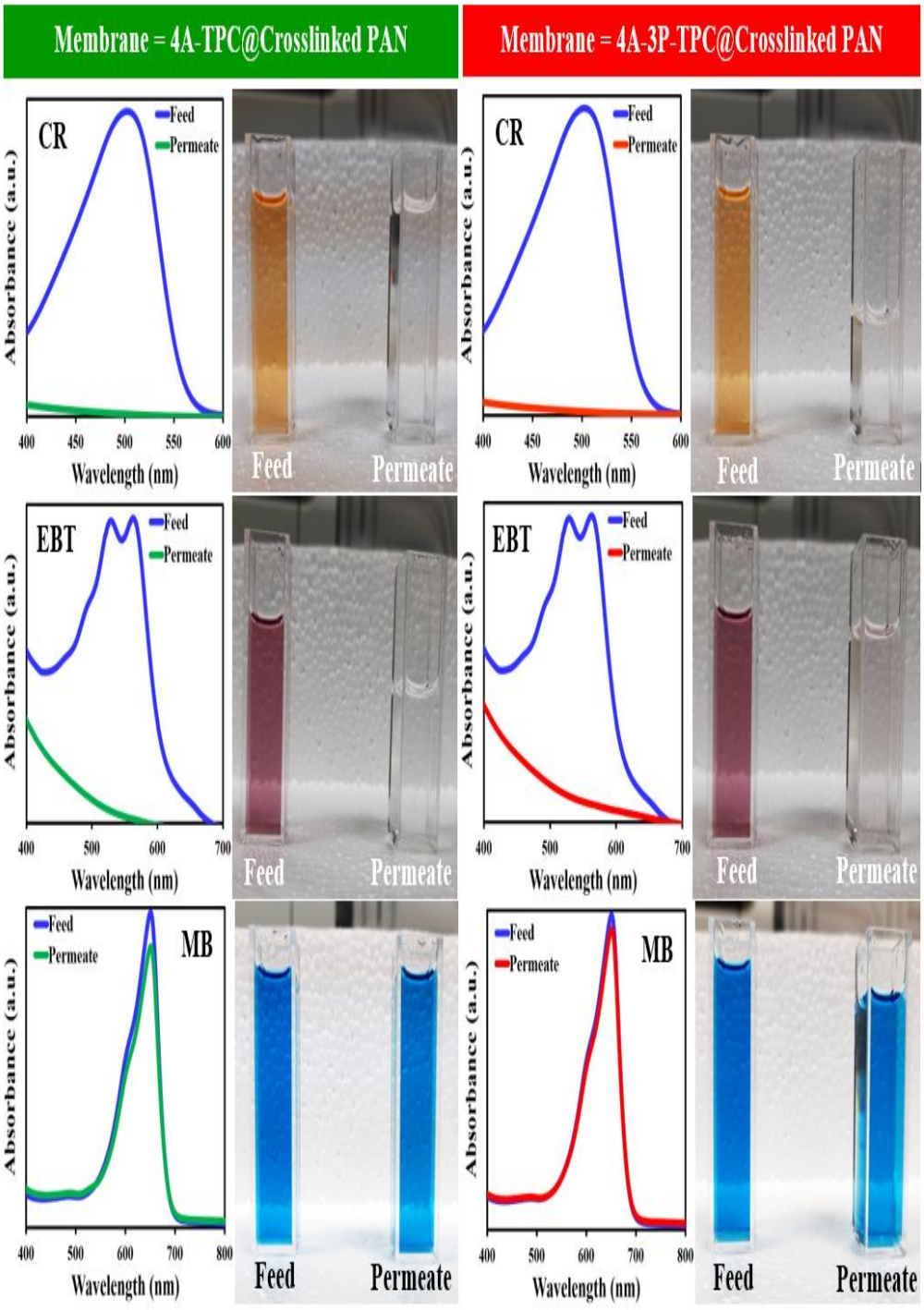


Figure 10. A comparison of absorption spectra and coloration of feeds and permeates of CR, EBT and MB collected during filtration experiments

10. Conclusion

Nanofiltration OSN membranes were successfully fabricated by using two different linear aliphatic amines 4A and 4A-3P amines on crosslinked PAN. The resultant OSN membranes 4A-TPC@Crosslinked PAN and (b) 4A-3P-TPC@Crosslinked PAN membrane were throughly characterized through SEM, WCA, EDX analysis, elemental mapping, ATR-FTIR and AFM microscopy. 4A-TPC@Crosslinked PAN membrane, the permeate flux of n-hexane and toluene was raised from 33.8 LMH to 81.1 LMH as the pressure was increased from 4 bar to 10 bar. The n-hexane and toluene showed a flux of 109.9 LMH and 95.5 LMH respectively. The CR showed highest rejection reaching to 99.1% for 4A-TPC@Crosslinked PAN membrane and 98.8% for 4A-3P-TPC@Crosslinked PAN membrane. In case of EBT, the rejection stayed at 99.1% for 4A-TPC@Crosslinked PAN membrane while it was slightly reduced for 4A-3P-TPC@Crosslinked PAN membrane reaching to 94.4%. Hence, a slight variation in the structure of the reacting monomers during IP alters the performance of the membrane during filtration experiemnts.

11. Risk and Safety precautions:

All of the risks were assessed and appropriate safety protocols were implemented. Using proper equipment, Personal protective equipment including: eye glasses, lab coat, gloves will be worn during the lab experiment, Make sure chemicals are properly labeled and stored.

References:

[1] Grodowska, K., & Parczewski, A. (2010). Organic solvents in the pharmaceutical industry. *Acta poloniae pharmaceutica*, *67*(1), 3–12.

[2] Martínez, M. B., Van der Bruggen, B., Negrin, Z. R., & Luis Alconero, P. (2012). Separation of a high-value pharmaceutical compound from waste ethanol by nanofiltration. *Journal of Industrial and Engineering Chemistry*, *18*(5), 1635-1641. doi:10.1016/j.jiec.2012.02.024

[3] S. Clare, Solvents and sustainability, Chemistry World. (2018). https://www.chemistryworld.com/features/solvents-and-sustainability/3008751.article

[4] Ferreira, Flávio, Leonor Resina, Teresa Esteves, and Frederico Castelo Ferreira. (2020). "Comparison and Combination of Organic Solvent Nanofiltration and Adsorption Processes: A Mathematical Approach for Mitigation of Active Pharmaceutical Ingredient Losses during Genotoxin Removal" *Membranes* 10, no. 4: 73. https://doi.org/10.3390/membranes10040073

[5] Wafi, M. K., Hussain, N., El-Sharief Abdalla, O., Al-Far, M. D., Al-Hajaj, N. A., & Alzonnikah, K. F. (2019). Nanofiltration as a cost-saving desalination process. *SN Applied Sciences*, *1*(7), 1-9.

[6] Geens, J., De Witte, B., & Van der Bruggen, B. (2007). Removal of API's (active pharmaceutical ingredients) from organic solvents by nanofiltration. *Separation Science and Technology*, *42*(11), 2435-2449.

[7] Cheng, X., Qin, Y., Ye, Y., Chen, X., Wang, K., Zhang, Y., ... & Drioli, E. (2021). Finely tailored pore structure of polyamide nanofiltration membranes for highly-efficient application in water treatment. *Chemical Engineering Journal*, *417*, 127976.

[8] Szekely, G., Jimenez-Solomon, M. F., Marchetti, P., Kim, J. F., & Livingston, A. G. (2014). Sustainability assessment of organic solvent nanofiltration: from fabrication to application. *Green Chemistry*, *16*(10), 4440-4473.

[9] Zhang, F., Fan, J. B., & Wang, S. (2020). Interfacial polymerization: From chemistry to functional materials. *Angewandte Chemie International Edition*, *59*(49), 21840-21856.

[10] Aboagye, E. A., Chea, J. D., & Yenkie, K. M. (2021). Systems level roadmap for solvent recovery and reuse in industries. *Iscience*, *24*(10), 103114.

[11] Huang, T., Moosa, B. A., Hoang, P., Liu, J., Chisca, S., Zhang, G., ... & Nunes, S. P. (2020). Molecularly-porous ultrathin membranes for highly selective organic solvent nanofiltration. *Nature communications*, *11*(1), 1-10.

[12] Mahdavi, H., & Karami, M. (2022). Cross-linked mixed matrix membranes made up of amine-functionalized silica and chloromethylated polysulfone for organic solvent nanofiltration applications. *Journal of Environmental Chemical Engineering*, *10*(2), 107145.

[13] Karan, S., Samitsu, S., Peng, X., Kurashima, K., & Ichinose, I. (2012). Ultrafast viscous permeation of organic solvents through diamond-like carbon nanosheets. *Science*, *335*(6067), 444-447.

[14] Cao, Y., Nakhjiri, A. T., & Ghadiri, M. (2022). Membrane desalination for water treatment: recent developments, techno-economic evaluation and innovative approaches toward water sustainability. *The European Physical Journal Plus*, *137*(7), 763.

[15] Li, X., Liu, Y., Wang, J., Gascon, J., Li, J., & Van der Bruggen, B. (2017). Metal–organic frameworks based membranes for liquid separation. *Chemical Society Reviews*, *46*(23), 7124-7144.

[16] Villalobos, L. F., Huang, T., & Peinemann, K. V. (2017). Cyclodextrin films with fast solvent transport and shape-selective permeability. *Advanced Materials*, *29*(26), 1606641.

[17] Zhang, Z., Kang, G., Yu, H., Jin, Y., & Cao, Y. (2019). From reverse osmosis to nanofiltration: Precise control of the pore size and charge of polyamide membranes via interfacial polymerization. *Desalination*, *466*, 16-23.

【評語】030033

Petroleum industry holds the key for modern society. In this research, the students construct a new membrane to help purification of the products as organic solvents. The student's presentation is impressive and the research results are good. It has potential for industrial application. Scale-up will be the critical factor.