

Reza Razavi,^a Alireza Shakeri,^a ^{*a} Hasan Salehi,^a Rozgol Bonsale,^b Amir Jangizehi^c
and Sebastian Seiffert ^{*c}

Received 18th June 2025,
Accepted 3rd November 2025

DOI: 10.1039/d5py00605h

rsc.li/polymers

Providing sufficient potable water is essential for the sustainability of industrial operations and human life. In light of rapid population growth and the limited availability of global freshwater resources, cost-efficient and rapid seawater desalination and wastewater treatment have become increasingly important to meet the demand for high-quality water across sectors.¹ The development of advanced processes with low operating costs and minimal energy consumption holds promise for enabling sustainable potable water production from unconventional sources.² Forward osmosis (FO) has recently attracted considerable attention as a novel membrane-based technology in both industrial applications and academic research.³ The FO process involves two solutions with differing osmotic pressures: the draw solution

(DS), which possesses a higher osmotic pressure, and the feed solution (FS), which has a lower osmotic pressure.⁴ During FO, the osmotic pressure gradient drives water to permeate through the FO membrane toward the DS side while limiting solute passage.⁵ The FO process is widely favored for its low energy consumption, high water recovery potential, and relatively low fouling propensity.^{6,7} These advantages make FO technology highly attractive and widely applied across diverse fields, including food processing, seawater desalination, power generation, pharmaceutical intermediate enrichment, and wastewater treatment.. Although FO offers several advantages over pressure-driven membrane technologies, it still encounters major limitations, including: (1) intrinsic membrane shortcomings, (2) difficulties in recovering water from diluted draw solutions, and (3) concentration polarization (CP) effects that obstruct industrial-scale application.⁸ Advancing high-performance membranes is considered a crucial step toward the successful commercialization of FO technology. Numerous studies have aimed to develop FO membranes that deliver high water permeability along with minimal reverse salt flux.^{9–11} Commonly, FO membranes are prepared using different approaches, such as (i) the layer-by-layer (LBL) self-assembly technique,¹² (ii) thin-film composite (TFC)

^a*School of Chemistry, College of Science, University of Tehran, 14155-6619 Tehran, Iran. E-mail: Alireza.shakeri@ut.ac.ir*

^bEnvironmental and Chemical Engineering Unit, Faculty of Technology, University of Oulu, Oulu, Finland

^cDepartment of Chemistry, Johannes Gutenberg University of Mainz, Duesbergweg 10-14, 55128 Mainz, Germany. E-mail: Sebastian.seiffert@uni-mainz.de



Sebastian Seiffert is a full professor for physical chemistry of polymers at Johannes Gutenberg-University Mainz. He is spokesperson of a DFG Research Unit on amphiphilic co-networks, of a BMBF Project on seawater desalination by hydrogels, and of a DFG Collaborative Research Center on defects in soft matter. He is also the author of several textbooks on physical chemistry and polymer science. Sebastian's work was honored with the

Based on this background, in this investigation, we developed a novel TFN-FO membrane utilizing PDMA-*graft*-GO (GO-*g*-PDMA) nanoplates as blending nanofillers. The GO-*g*-PDMA nanofillers were successfully prepared *via* a click reaction by grafting alkynyl-PDMA brushes onto GO-N₃ nanoplates, and the resulting nanofillers were thoroughly analyzed. Five nanocomposite substrates were then constructed by incorporating GO and GO-*g*-PDMA in varying amounts *via* the NIPS method. Subsequently, the PA rejection layer was established on the nanocomposite substrates to obtain the TFN-FO membranes. We examine in detail the effects of GO or GO-*g*-PDMA nanofillers on the substrate and PA active-layer properties, including further assessment of how variations in the substrate and PA rejection layer influence the FO efficiency of the TFN-FO membranes.

Graphite powder, supplied by Alfa Aesar Company, was used for the synthesis of GO nanoplates. Potassium permanganate (KMnO_4 , 99%), sulfuric acid (H_2SO_4 , 98%), hydrogen peroxide (H_2O_2 , 30%), phosphoric acid (H_3PO_4 , 99%), and hydrochloric acid (HCl , 37%) were procured from Merck and employed in the preparation of GO nanoplates. Sodium azide (NaN_3 , Merck), (3-glycidyloxypropyl) trimethoxysilane (GPTMS, Merck), and ethanol ($\text{C}_2\text{H}_5\text{OH}$, $\geq 99.9\%$, Merck) were used to synthesize azide-functionalized GO (GO-N_3) nanoplates. For the synthesis of alkyne-terminated PDMA polymer, propargyl

initiator (Fig. 1a). Specifically, 103 mg (0.5 mmol) of PBIb, 7.86 g (50 mmol) of DMA, 35.8 mg (0.25 mmol) of CuBr, and 104 μ L (0.5 mmol) of PMDETA were combined in a 50 mL Schlenk flask containing 20 mL of dry DMF. The reaction system was degassed three times using a freeze-pump-thaw cycle, followed by ATRP polymerization at 80 $^{\circ}$ C for 12 h. The polymerization was terminated by adding 100 mL of water, and the reaction mixture was heated to 80 $^{\circ}$ C to induce precipitation of the PDMA polymer. For further purification, the PDMA polymer was dissolved in THF and passed through an alumina column to remove any residual Cu⁺. The purified polymer solution was then concentrated by rotary evaporation and precipitated with hexane as the nonsolvent. ¹HNMR (CDCl₃): 1.0 ppm (9H, -CH₃), 1.8 ppm (2H, -CH₂-), 2.4 ppm (6H, -N(CH₃)₂), and 2.6 ppm (2H, -N-CH₃).³⁶

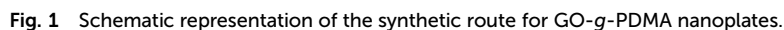
2.5. Preparation of GO-g-PDMA nanoplates

In this study, alkynyl-PDMA chains were grafted onto GO-N₃ nanoplates at a 1 : 1 mass ratio of GO to PDMA *via* a click reaction. To initiate the process, 0.6 g of GO-N₃ was dispersed in 20 mL of DMF containing 0.6 g (0.23 mmol) of alkyne-terminated PDMA, 0.025 g (0.18 mmol) of CuBr, and 0.04 g (0.23 mmol) of PMDETA, while nitrogen was bubbled through the mixture. The reaction proceeded at 25 °C for 72 h. Following the grafting step, the resulting PDMA-functionalized GO nanoplates were isolated by centrifugation (5000 rpm for 10 min), thoroughly rinsed with DMF and DI water, and subsequently dried in a vacuum oven at 50 °C. The final product was labeled as GO-*g*-PDMA.

2.6. Preparation of the nanocomposite substrates

In this work, all substrates, both pristine and nanocomposite, were fabricated using the conventional NIPS method. PES was employed as the polymer support, anhydrous NMP as the solvent, PEG-400 as the pore-forming agent, and GO or GO-g-PDMA as the nanofillers. DI water was used as the non-solvent coagulation bath. Prior to solution preparation, PES powder was dried at 70 °C for 12 hours to eliminate any surface-adsorbed moisture. A predetermined amount of nanoplates (either GO or GO-g-PDMA) was dispersed into a premixed solution of NMP and PEG, followed by 2 hours of sonication to ensure a stable, uniform suspension. Subsequently, PES powder was added to the casting solution and dissolved at 80 °C under continuous stirring. After complete dissolution, the solution was left undisturbed overnight to allow any trapped air bubbles to escape. The degassed casting solution was then cast onto a clean glass plate using a doctor blade with a 100 μm gap, and the plate was immediately immersed in a DI-water bath for 1 hour. Once solidified, the flat sheet substrates were transferred to a fresh DI-water coagulation bath and soaked for 24 hours to guarantee thorough solvent exchange between NMP and DI-water. Finally, the resulting substrates were stored in DI-water until further use in the IP reaction and characterization steps.

In this work, an alkyne-terminated PDMA homopolymer was synthesized *via* ATRP using alkyne-terminated PBiB as the



onto a clean glass plate and soaked in the MPD solution for 2 minutes. After removing residual MPD droplets from the substrate surface using an air knife, the MPD-absorbed substrate was immersed in the TMC solution for 90 seconds to form the PA thin film. To remove unreacted TMC monomer, the formed PA skin layer was gently rinsed with *n*-hexane. The fabricated TFN membrane was then placed in an oven at 60 °C for 1 minute to ensure the formation of a stable, cross-linked PA active layer. After

Substrate porosity (ε , %) was determined using the gravimetric method. Substrates were removed from DI water, surface water was gently blotted, and they were immediately weighed. Samples were then dried at 50 °C until constant weight was achieved. Porosity was calculated using eqn (1):

$$\varepsilon = \frac{(m_w - m_d)/\rho_w}{(m_w - m_d)/\rho_w + m_d/\rho_p} \quad (1)$$

where m_w and m_d are the weights of wet and dry substrates, respectively; ρ_w is the density of water (1.0 g cm^{-3}); and ρ_P is the density of PES (1.37 g cm^{-3}).

The pure water permeability (PWP) test was conducted to evaluate the substrate hydrophilicity by measuring water flux through the substrate. All tests were performed on substrates with an effective surface area of 4.9 cm², using a custom-made cross-flow module. During the measurement, deionized (DI) water was used as the feed solution, and the substrate was subjected to a hydraulic pressure of 5 bar at 25 °C. The PWP value was calculated using eqn (2):

$$\text{PWP} = \frac{V}{A_m \times \Delta t} \quad (2)$$

where V is the volume of permeate collected (L), A_m is the effective membrane area (m^2), and Δt is the test duration (h). Using the porosity and PWP data, the average pore radius r_p (nm) of the substrates was calculated *via* the Guerout-Elford-Ferry equation (eqn (3)):

$$r_p = \sqrt{\frac{(2.9 - 1.75\varepsilon) \times 8Q\eta T}{\varepsilon}} \quad (3)$$

The PWP value, expressed as Q ($\text{m}^3 \text{s}^{-1}$), represents the volumetric flow rate of the permeate and is influenced by the applied external hydraulic pressure ΔP (Pa). In the Guerout–Elford–Ferry equation, T (cm) corresponds to the substrate thickness, and η (Pa s) denotes the dynamic viscosity of water at room temperature.

The FO performance of the fabricated TFC and TFN membranes was evaluated using a lab-developed cross-flow FO permeation system with an effective membrane surface area of 4.9 cm². Key performance parameters were measured, including water flux (J_w , LMH), reverse salt flux (J_s , gMH), and membrane selectivity (J_s/J_w), following established protocols. All tests were conducted at 25 °C using aqueous NaCl solutions at varying concentrations (0.5, 1.0, 1.5, and 2.0 M), with deionized water serving as the FS or DS depending on the test mode. The permeation cell operated at a cross-flow rate of 100 mL min⁻¹. Membrane performance

The surface roughness of the substrates and PA thin layers was measured in tapping mode using atomic force microscopy (AFM, Solver, NT-MDT). Membrane samples ($\sim 2 \text{ cm}^2$) were fixed to the sample holder and scanned over a $5 \text{ }\mu\text{m} \times 5 \text{ }\mu\text{m}$ area. Membrane hydrophilicity was evaluated by water contact angle (WCA) measurements using the sessile drop method with a goniometer (CAG-20 SE, JIKAN, Iran). Membranes were

was examined in both FO mode (where the PA rejection layer faces the FS) and PRO mode (where the PA rejection layer faces the DS). Each FO test was run for approximately 30 minutes to ensure system stabilization, after which water flux and reverse salt flux data were recorded. To ensure reproducibility, each membrane was tested three times.

Water flux, J_w , was calculated by measuring the change in FS mass over time using a digital balance, according to eqn (4):

$$J_w = \frac{\frac{\Delta m_F}{\rho_F}}{A_m \times \Delta t} \quad (4)$$

where Δm_F is the change in FS mass (kg), ρ_F is the density of the FS at room temperature (kg m^{-3}), Δt is the duration of the test (s), and A_m is the effective membrane area (m^2).

Reverse salt flux, J_s , was calculated based on conductivity measurements of the FS using a conductivity meter (WTW GmbH, Germany) and according to eqn (5):

$$J_s = \frac{V_t C_t - V_0 C_0}{A_m \times \Delta t} \quad (5)$$

where V_0 and V_t are the FS volumes (L) before and after the FO test, respectively, and C_0 and C_t are the corresponding FS salt concentrations (g L^{-1}).

2.12. Evaluation of the membrane's intrinsic characteristics

Water permeability (A , LMH per bar) and salt rejection (R_s) of the as-fabricated TFC and TFN membranes were evaluated using a constant-pressure dead-end reverse osmosis (RO) permeation setup. Membrane coupons of 3.14 cm^2 were cut from each wet membrane and mounted in the RO system. DI water and 1000 ppm NaCl solution were pressurized to 5 bar across the PA active layer to determine the water permeability and

salt rejection. Prior to each measurement, membranes were stabilized for 20 minutes. All experiments were conducted at 25°C for 1 hour, with each test repeated three times using different membrane coupons. Water permeability J was calculated based on the volume of permeated DI water using eqn (6):

$$J = \frac{\Delta V}{A_m \times \Delta t \times \Delta P} \quad (6)$$

where ΔV (L) is the volume of permeate collected, A_m (m^2) is the effective membrane area, Δt (h) is the time interval, and ΔP (bar) is the applied hydraulic pressure. Salt rejection (R_s) was determined using the conductivity measurements of the feed and permeate solutions according to eqn (7):

$$R_{\text{NaCl}} = \left(1 - \frac{C_p}{C_f}\right) \times 100 \quad (7)$$

where C_f and C_p (ppm) are the salt concentrations in the feed and permeate, respectively. The salt permeability coefficient B (LMH) was calculated by fitting the rejection data into eqn (8):

$$\frac{1 - R_s}{R_s} = \frac{B}{A(\Delta P - \Delta \pi)} \quad (8)$$

where $\Delta \pi$ (bar) is the osmotic pressure difference across the membrane. Furthermore, the membrane structural parameter S (μm), which reflects internal concentration polarization, was estimated by fitting the measured A and B values to eqn (9). In this equation, π_D and π_F represent the osmotic pressures of the draw and feed solutions, respectively, and D is the salt diffusion coefficient.

$$S = \frac{D_s}{J_w} \ln \frac{A\pi_D + B}{A\pi_F + J_w + B} \quad (9)$$

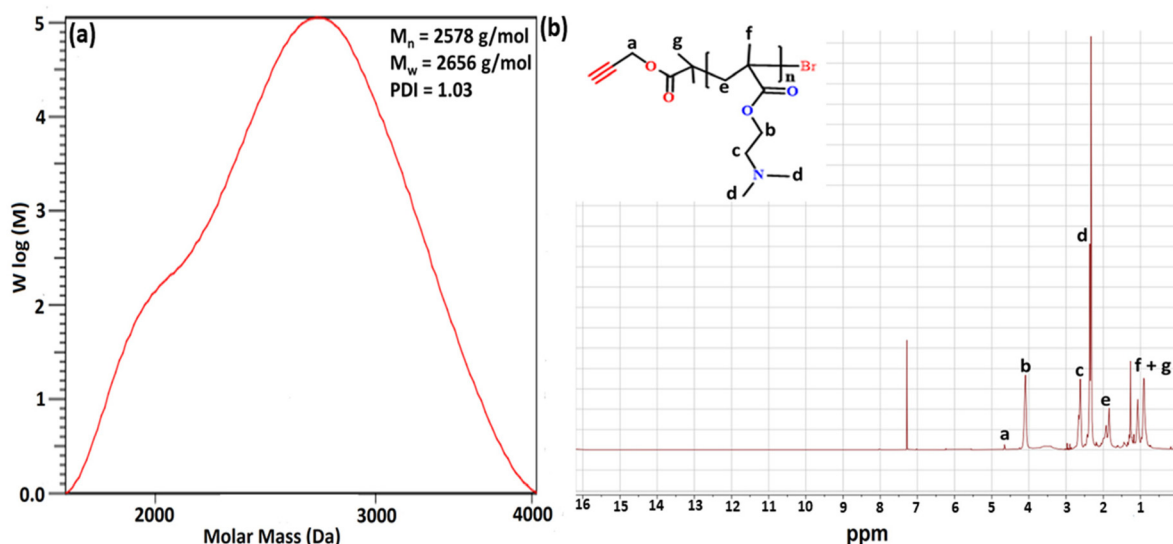


Fig. 2 (a) GPC chromatogram and (b) ^1H NMR spectrum of the alkynyl-terminated PDMA polymer.

3. Results and discussion

3.1. Preparation of GO-g-PDMA

In this study, GO-g-PDMA nanoplates were synthesized *via* a click reaction between alkyne-terminated PDMA and azide-functionalized GO. The overall synthetic route is illustrated in Fig. 1. Alkyne-terminated PDMA was synthesized by ATRP using PBiB as the initiator. GPC analysis of the obtained polymer (Fig. 2a) reveals a number-average molecular weight of 2578 g mol^{-1} and a weight-average molecular weight of 2656 g mol^{-1} , indicating a narrow molecular weight distribution of 1.03. The chemical structure of the synthesized PDMA was further confirmed by ^1H NMR spectroscopy (Fig. 2b), which shows characteristic signals corresponding to the polymer backbone and side groups. The spectrum validated successful polymerization and purification of the alkyne-terminated PDMA.

Azide-functionalized GO (GO- N_3) was synthesized in two steps. First, graphene oxide was reacted with (3-glycidyloxypropyl)trimethoxysilane (GPTMS) to introduce epoxy groups *via* silanization of the GO surface. In the second step, the epoxy-

functionalized GO was reacted with sodium azide to form azide groups on the GO surface. The successful synthesis of GO- N_3 and subsequent grafting of PDMA chains onto GO *via* the click reaction were verified using several techniques including FTIR, XRD, TGA, FE-SEM and EDS analyses.

FTIR. In the FTIR spectrum of the synthesized GO *via* the modified Hummers' method, characteristic absorption peaks are observed at 3300 cm^{-1} (O-H stretching vibration), 1725 cm^{-1} (C=O stretching vibration), 1040 cm^{-1} (C-O stretching vibration), and 1615 cm^{-1} (C=C stretching in aromatic rings).³⁷ These typical peaks also appear in the spectra of GO- N_3 and GO-g-PDMA nanoplates, confirming the preservation of the fundamental GO structure after functionalization. However, their intensities decrease markedly in the GO- N_3 and GO-g-PDMA samples, likely due to the partial reduction of oxygenated groups during azide modification and PDMA grafting. As shown in Fig. 3a, new absorption peaks emerge at 1095 and 2090 cm^{-1} in the GO- N_3 spectrum, which correspond to the Si-O-Si stretching and azide ($-\text{N}_3$) stretching vibrations, respectively. These features verify the successful introduction of GPTMS and azide groups onto the GO surface. Additionally,

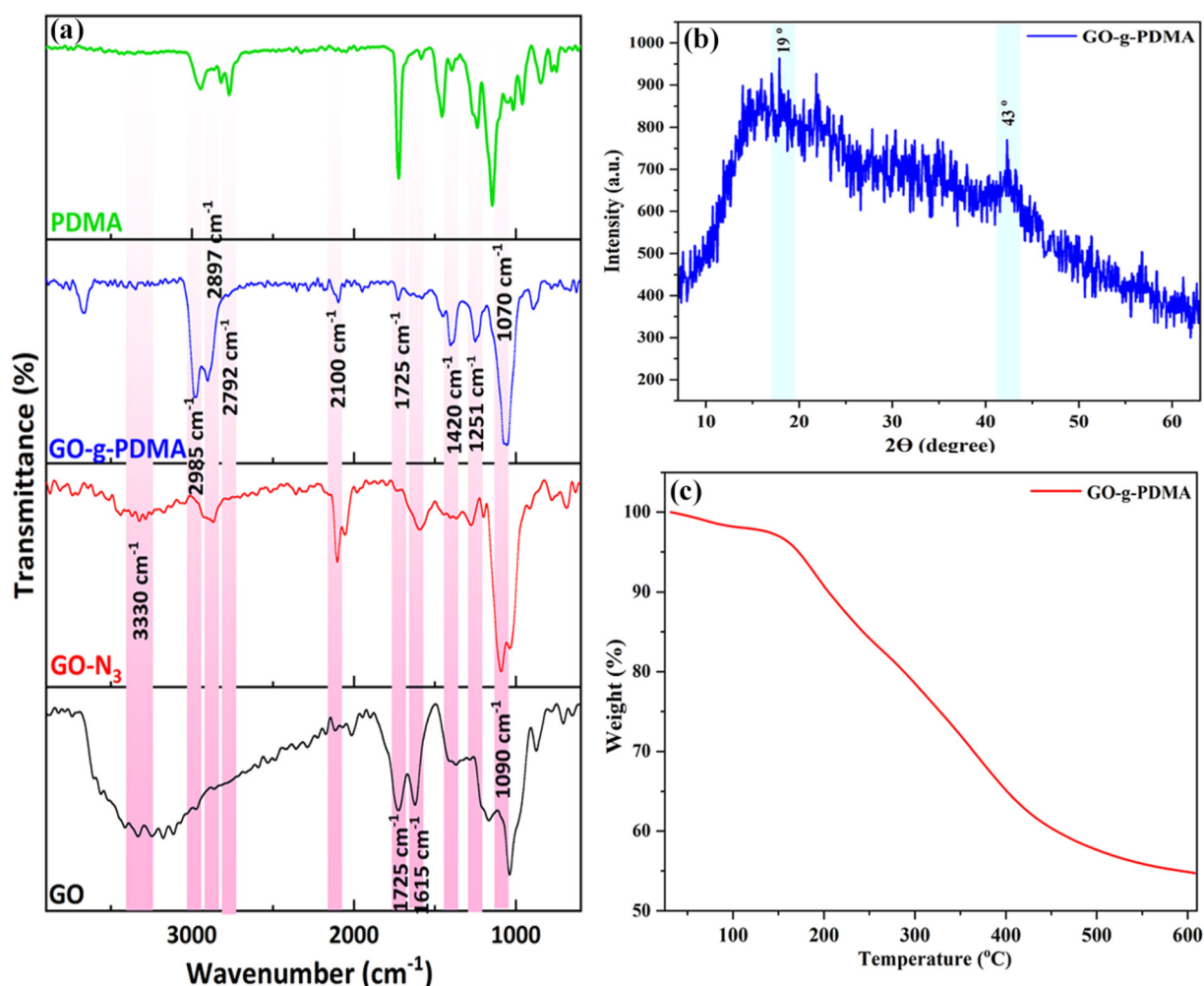
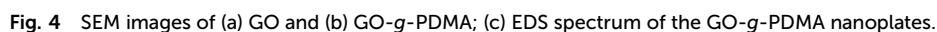


Fig. 3 (a) Comparison of FTIR spectra of the GO, GO- N_3 , GO-g-PDMA, and PDMA polymer, (b) XRD pattern, and (c) TGA curve of the GO-g-PDMA.



SEM images and EDS analysis. SEM was used to examine morphological changes in GO after PDMA functionalization. As shown in Fig. 4a, pristine GO typically exhibits a crumpled, sheet-like morphology with a relatively smooth surface. The presence of oxygen-containing functional groups introduces wrinkles and folds that disrupt the intrinsic planar structure of graphene sheets.⁴² Upon grafting PDMA onto the GO surface, as illustrated in Fig. 4b, a notable increase in surface roughness was observed. This appears in the SEM images as a more textured morphology, with visible protrusions and surface irregularities attributed to the presence of polymer chains. Complementary to the SEM results, EDS analysis (Fig. 4c) detected the presence of nitrogen (N) and bromine



All PES-based substrates containing GO and GO-*g*-PDMA were analyzed using ATR-FTIR spectroscopy, and the recorded spectra are shown in Fig. 5(a). The spectra of all fabricated substrates exhibit characteristic bands corresponding to the

In this study, PES substrates were modified using GO-*g*-PDMA at three different loadings. For comparison, an additional PES

Substrates	PES (g)	NMP (g)	PEG-400 (g)	Nanofiller type	Content ^a (g)	Corresponding FO membranes
PES	3.0	13.0	4.0	—	0.0	TFC
PES-GO _{0.5}	3.0	13.0	3.9	GO	0.1	TFN-GO _{0.5}
PES-GOP _{0.25}	3.0	13.0	3.95	GO- <i>g</i> -PDMA	0.05	TFN-GOP _{0.25}
PES-GOP _{0.5}	3.0	13.0	3.9	GO- <i>g</i> -PDMA	0.1	TFN-GOP _{0.5}
PES-GOP ₁	3.0	13.0	3.8	GO- <i>g</i> -PDMA	0.2	TFN-GOP ₁

(a) FTIR spectra of PES-GOP films with varying GOP content (0, 0.25, 0.5, 1) and pure PES. The x-axis represents Wavenumber (cm^{-1}) from 2000 to 1000, and the y-axis represents Transmittance (%). Key peaks are labeled at 1576 cm^{-1} , 1483 cm^{-1} , 1296 cm^{-1} , 1010 cm^{-1} , 401 cm^{-1} , 1321 cm^{-1} , 1239 cm^{-1} , 1149 cm^{-1} , and 1103 cm^{-1} .

(b) FTIR spectra of TFN-GOP films with varying GOP content (0, 0.2, 0.5) on a PES substrate, showing the PA layer. The x-axis represents Wavenumber (cm^{-1}) from 1500 to 1000, and the y-axis represents Transmittance (%). Key peaks are labeled at 1666 cm^{-1} , 1608 cm^{-1} , and 1542 cm^{-1} .

(c) Zoomed-in FTIR spectra of PES-GOP films in the 1600-1300 cm^{-1} range. The x-axis represents Wavenumber (cm^{-1}) from 1600 to 1300, and the y-axis represents Transmittance (%). The spectra show the characteristic peak at 1615 cm^{-1} for PES-GOP_{0.25} (black), PES-GOP_{0.5} (blue), and PES-GOP₁ (red).

This journal is © The Royal Society of Chemistry 2026

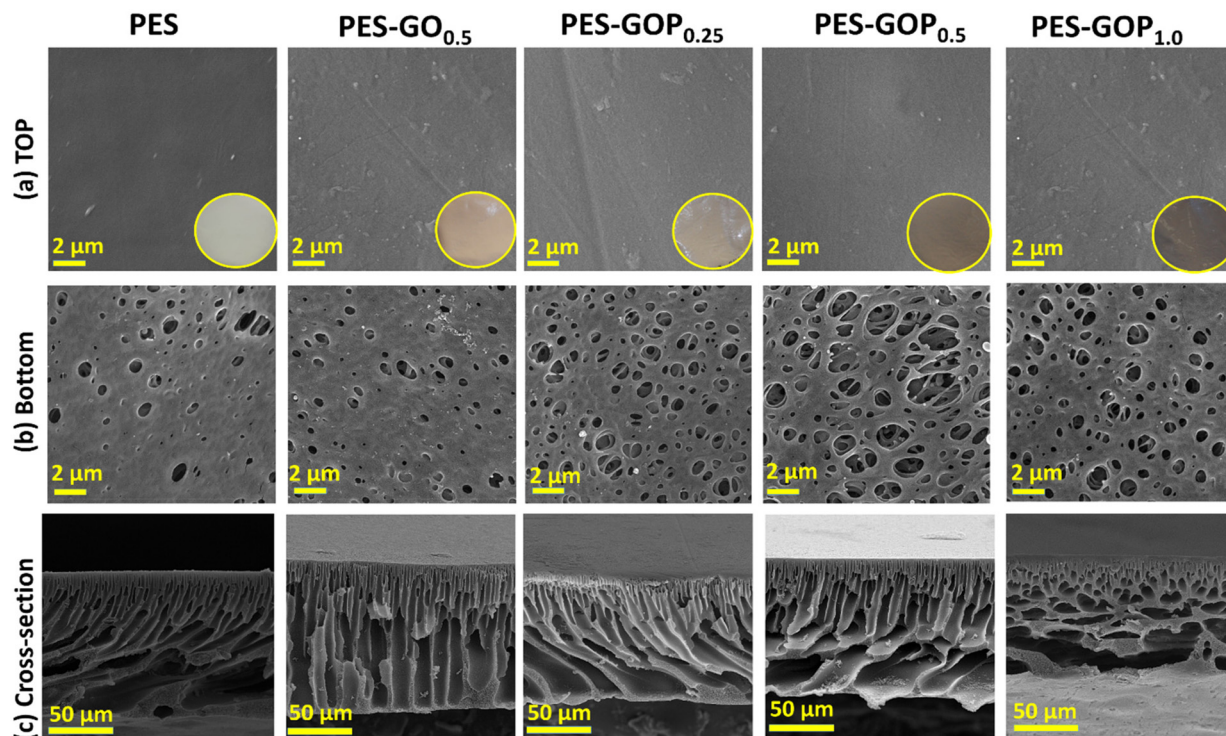


Fig. 6 (a) SEM images of the top surface morphologies and corresponding digital photographs of the substrates; (b) SEM images of the bottom surface morphologies; and (c) cross-sectional SEM images of the substrates.

PES polymer. Specifically, the bands at 1483, 1296, and 1239 cm^{-1} are attributed to the vibrations of aromatic rings, asymmetric stretching of $\text{O}=\text{S}=\text{O}$, and $\text{C}-\text{O}-\text{C}$ vibrational bonding, respectively. Further analysis of the ATR-FTIR spectra of the support layers revealed that the peak at 1615 cm^{-1} became more intense as the GO-g-PDPA nanofiller concentration increased (Fig. 5c). This peak corresponds to the stretching vibrations of aromatic groups in the GO nanofiller. This spectroscopic finding likely explains the darker coloration of the support layers as nanofiller concentrations increase (Fig. 6a).

The effect of GO-g-PDPA incorporation on membrane morphology was investigated using SEM images. All substrates were fabricated using the conventional NIPS process, in which the NMP solvent in the cast polymeric film was exchanged with water (the non-solvent) to form a solid membrane. The NIPS rate critically affects the substrate structure. Most studies indicate that hydrophilic nanofillers enhance the casting solution's tolerance to water content, thereby slowing the NIPS rate.⁴³ Consequently, the incorporation of GO-g-PDPA is anticipated to substantially affect the structure of the modified PES substrates. As shown in Fig. 6a, the top surfaces of all substrates appear relatively smooth, with no visible GO or GO-g-PDPA nanosheets. This contrasts with membranes containing non-carbon nanofillers, such as silica⁴⁴ and TiO_2 ,⁴⁵ where nanofillers are typically visible on the membrane surface following the NIPS process. Similarly, other carbon-based nanofillers, such as GO-g-PHEMA,³¹ QGO,²⁵ and CNTs,⁴⁶ exhibit no

surface accumulation. This suggests that the carbonaceous nature of GO nanosheets and the PES polymer ensures effective dispersion of GO within the polymer matrix, preventing agglomeration on the membrane surface.⁴⁷ Additionally, the photographs in Fig. 6a illustrate that the substrate color gradually darkens with increasing nanofiller concentrations.

The morphology of the bottom surface of FO membranes directly influences water and solute diffusion through the substrate pores, so it is essential to analyze the structural changes that occur when hydrophilic nanofillers are added. Fig. 6(b) presents SEM images of the bottom surfaces of all substrates, revealing significant morphological modifications. The pore sizes on the bottom side of GO or GO-g-PDPA-modified substrates are considerably larger than those of the unmodified substrate. This variation in pore size can be attributed mainly to two factors: (1) the interfacial affinity between the glass plate and the casting solution, and (2) the interval between gelation initiation and film detachment.⁴⁸ Since a porous substrate helps mitigate ICP, it is reasonable to expect that the modified substrates will exhibit enhanced performance in FO processes.

Cross-sectional SEM images provide further insights into the impact of nanofillers on substrate morphology. As shown in Fig. 6c, all substrates exhibit two distinct regions: a dense top layer and a porous bottom layer, characteristic of membranes formed *via* the NIPS process.⁴⁹ The unmodified PES substrate exhibits irregular pore structures in the cross-section, resulting from rapid solvent-nonsolvent (NMP-water)



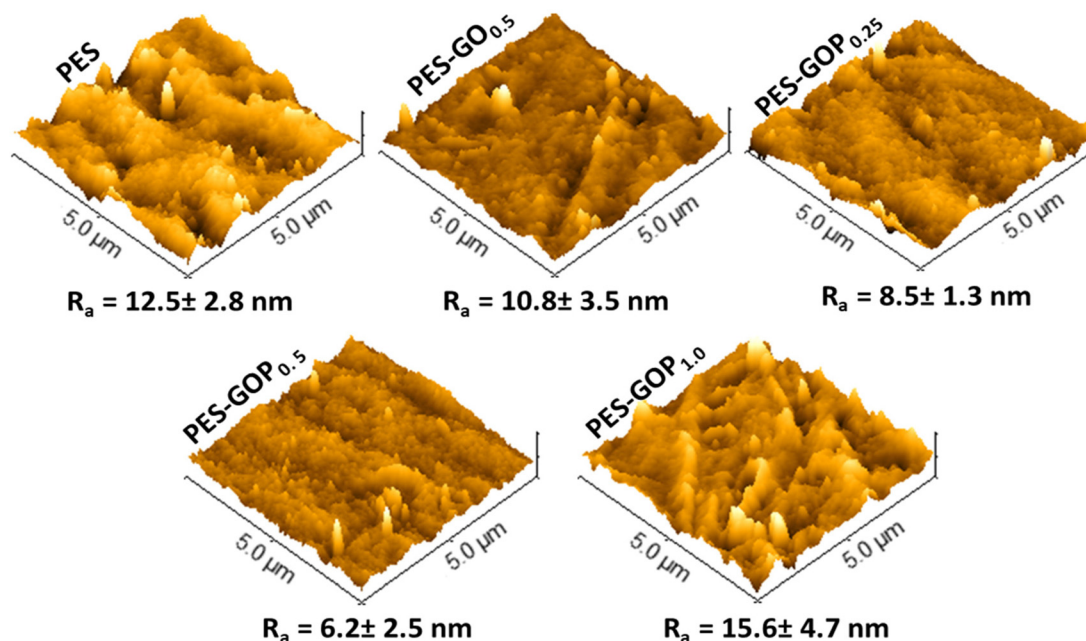


Fig. 7 Three-dimensional AFM images of PES substrates modified with GO and GO-*g*-PDMA nanofillers, showing variations in surface roughness.

exchange during phase inversion, driven by PES's intrinsic hydrophobicity.⁵⁰ In contrast, substrates modified with GO or GO-*g*-PDMA demonstrate significantly larger and more uniform pores throughout the cross-section. Increasing the GO-*g*-PDMA content encourages the creation of elongated finger-like pores, probably because the hydrophilic groups in GO and GO-*g*-PDMA reduce the solvent-nonsolvent exchange rate during NIPS, thereby promoting pore formation. However, at a higher GO-*g*-PDMA concentration of 1.0 wt%, the morphology shifts from finger-like to sponge-like, accompanied by a decrease in porosity. This change is likely due to the aggregation of GO-*g*-PDMA nanosheets at elevated loadings, which reduces their ability to effectively influence the phase inversion process.

In addition to influencing morphology, nanofillers also affect the surface roughness of membranes. Fig. 7 shows three-dimensional surface images of PES, PES-GO_{0.5}, PES-GOP_{0.25}, PES-GOP_{0.5}, and PES-GOP₁ substrates. The average surface roughness (R_a , nm) values are reported alongside the images. The pure PES substrate exhibits a relatively rough surface, with an R_a value of 12.5 ± 2.8 nm, which is higher than that of the GO and GO-*g*-PDMA-modified PES substrates. This reduction in roughness is likely due to the hydrophilic nanofillers at the surface, which contribute to a more controlled NIPS process and result in smoother membranes. However, at the highest nanofiller loading in PES-GOP₁, the R_a value increases again to an approximate value similar to that of bare PES. This increase could be due to nanofiller agglomeration, which decreases the uniformity of nanofiller coverage on the substrate surface and consequently impacts roughness.

The addition of nanofillers to the PES substrate also alters the intrinsic membrane properties, such as porosity, mean

pore size, hydrophilicity, and pure water permeability (PWP). The porosity of the substrates is measured using the gravimetric method, and the results are shown in Fig. 8a. Increasing the GO-*g*-PDMA loading from 0 to 0.5 wt% significantly enhances the porosity of the PES matrix, increasing it from $74.4 \pm 1.5\%$ to $82.6 \pm 1.1\%$. This increase in porosity can be attributed to several mechanisms: (1) the intercalation of GO-*g*-PDMA nanosheets into the PES polymer chains, which causes structural modification of the matrix, and (2) the inherent hydrophilicity of GO-*g*-PDMA nanosheets, which improves the overall hydrophilicity of the casting solution, affecting NIPS during substrate formation and resulting in a more porous structure.⁴³ However, when the GO-*g*-PDMA loading exceeds the optimal 0.5 wt% and reaches 1.0 wt%, a slight decrease in porosity is observed ($78.4 \pm 1.2\%$). This reduction likely results from increased viscosity of the casting solution, which affects the NIPS process, and from potential pore blockage due to excessive nanosheet aggregation. To further assess the effect of PDMA grafting on porosity enhancement, pristine GO nanosheets are also incorporated into the PES matrix at 0.5 wt%. The resulting porosity for the PES-GO_{0.5} sample (78.03%) is higher than that of the pure PES substrate but lower than that of the PES-GOP_{0.5} substrate. This result suggests that polymer grafting on the GO surface significantly improves the nanofiller's ability to enhance porosity. The presence of grafted PDMA chains improves compatibility between the GO nanosheets and the PES matrix, thereby minimizing aggregation and promoting a more uniform dispersion throughout the substrate.

In addition to porosity, Fig. 8a also shows the WCA measurements of the substrates, which serve as an indicator of surface hydrophilicity. The hydrophilicity of a substrate plays a



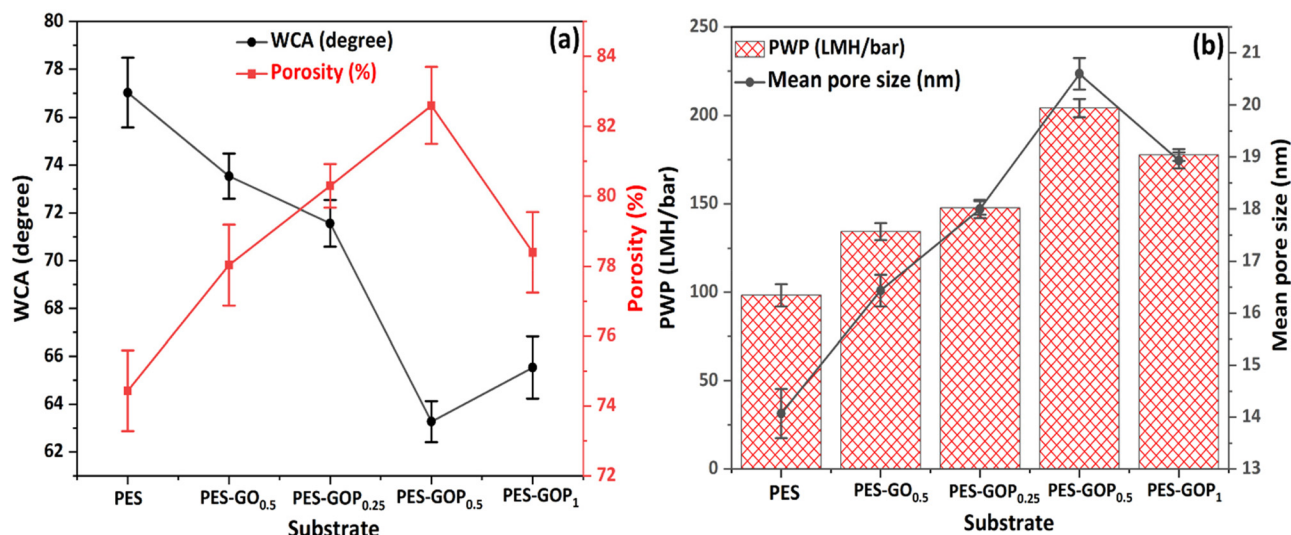


Fig. 8 (a) Porosity and water contact angle of unmodified and nanofiller-modified PES substrates. (b) Pure water permeability and mean pore size of the corresponding substrates.

crucial role in determining water flux. For the PES-GO_{0.5} substrate, the presence of oxygen-containing functional groups in GO nanosheets reduces the WCA to $73.5^\circ \pm 0.94$. A more pronounced decrease in WCA is observed when GO-g-PDMA nanosheets are incorporated, particularly up to 0.5 wt%, indicating a substantial improvement in surface hydrophilicity. Specifically, the WCA of the unmodified PES substrate was recorded as $77.0^\circ \pm 1.45$, which decreased to $63.2^\circ \pm 0.86$ in the PES-GOP_{0.5} substrate. This reduction is mainly due to the inherent hydrophilicity of GO-g-PDMA nanosheets, which is provided by the polar functional groups in the PDMA chains. PDMA possesses tertiary amine groups ($-\text{N}(\text{CH}_3)_2$) and ester groups ($-\text{COO}$), which can form strong dipole-dipole interactions with water molecules, thereby improving the wettability of the substrate surface. Notably, the WCA decrease is more substantial in the PES-GOP_{0.5} sample than in the PES-GO_{0.5} sample, which contains unmodified GO. This enhanced hydrophilicity is attributed to improved compatibility between the GO nanosheets and the PES matrix resulting from PDMA grafting.⁵¹ The polymeric modification enhances nanosheet dispersion and reduces aggregation, resulting in a more homogeneously hydrophilic surface and improved overall membrane performance.

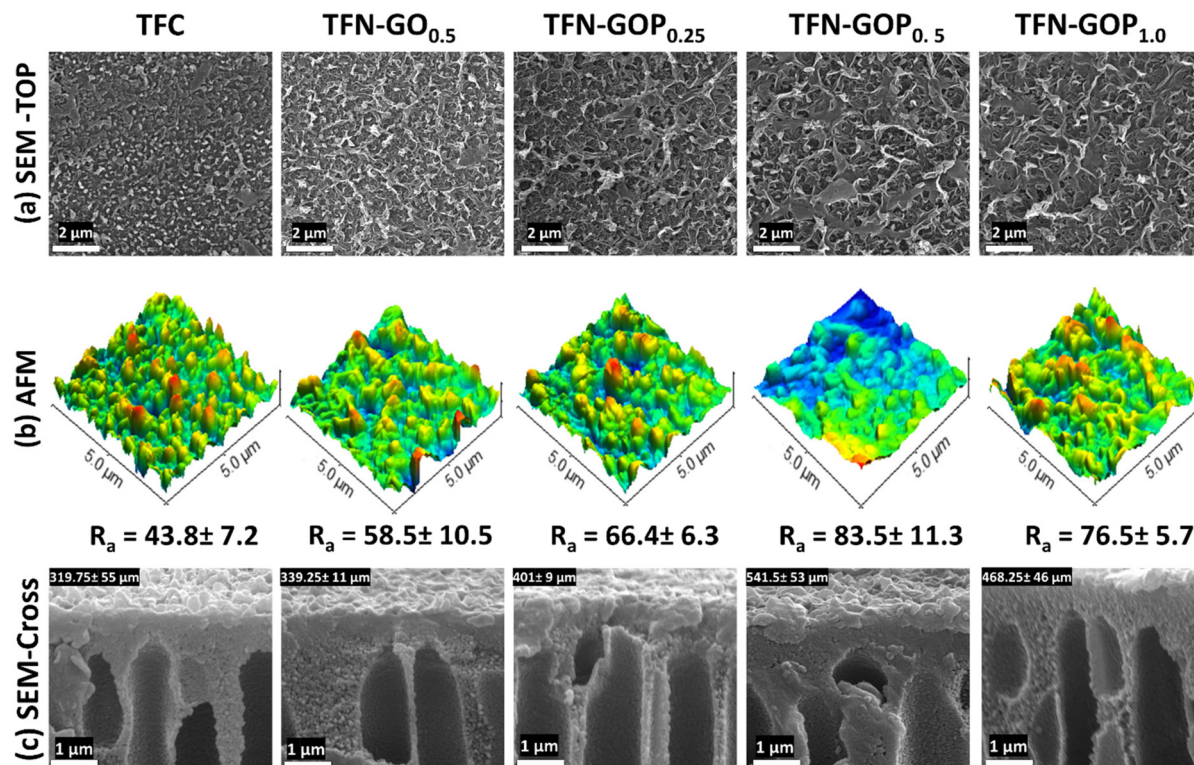
The mean pore size and PWP are other key substrate properties influenced by the nanofillers. The pore size trend is similar to the porosity trend, which shows that by increasing the nanofiller content, both porosity and mean pore size are enhanced simultaneously. As shown in Fig. 8b, the PWP of the PES-GO_{0.5} substrate reaches 134.4 ± 4.7 LMH per bar, representing an increase of approximately 36% compared to the unmodified PES substrate (98.3 ± 6.3 LMH per bar). Remarkably, the PES-GOP_{0.5} substrate exhibits the highest PWP value of 204.1 ± 5.2 LMH per bar, more than twice that of the pristine PES. Several mechanisms contribute to this

enhancement in permeability: (1) increased porosity facilitates more efficient water transport through the membrane matrix, (2) enhanced surface hydrophilicity promotes water adsorption and diffusion, (3) the formation of well-developed finger-like pores optimizes water flow pathways; and (4) the GO-g-PDMA nanofillers function as hydrophilic nanochannels, enabling additional water transport routes.⁵²

3.3. Influence of substrate modification on the PA active layer

The PA active layer in TFC-FO membranes is responsible for selective water transport while rejecting solutes. In this study, all PA layers were fabricated using the same IP method on different PES-based substrates. However, notable variations in the structure and properties of the PA layers were observed depending on the substrate. As with the substrates, the TFC and TFN membranes were characterized using ATR-FTIR spectroscopy. Because the ATR-FTIR beam penetration depth was approximately 1 μm and the thickness of the PA layer was about 400 nm, characteristic peaks from the substrates were also detectable. Nonetheless, all TFN membranes display distinct peaks at 1540 cm^{-1} , 1610 cm^{-1} , and 1660 cm^{-1} , which correspond to N-H in-plane bending (amide II), C=C aromatic ring stretching, and C=O stretching (amide I), respectively.⁵³ The presence of these peaks confirms the successful formation of the PA selective layer.

In general, the morphology of the PA layer changes depending on the substrate, as shown in Fig. 9a. The formation of the PA layer generally proceeds through two stages: initially, MPD reacts with TMC at the water-organic interface to form an ultra-thin, nodular PA layer. Then, the Marangoni effect enhances the transport of MPD toward the organic phase, restructuring the nascent layer into a characteristic ridge-and-valley morphology. On the unmodified PES substrate (TFC), the PA layer



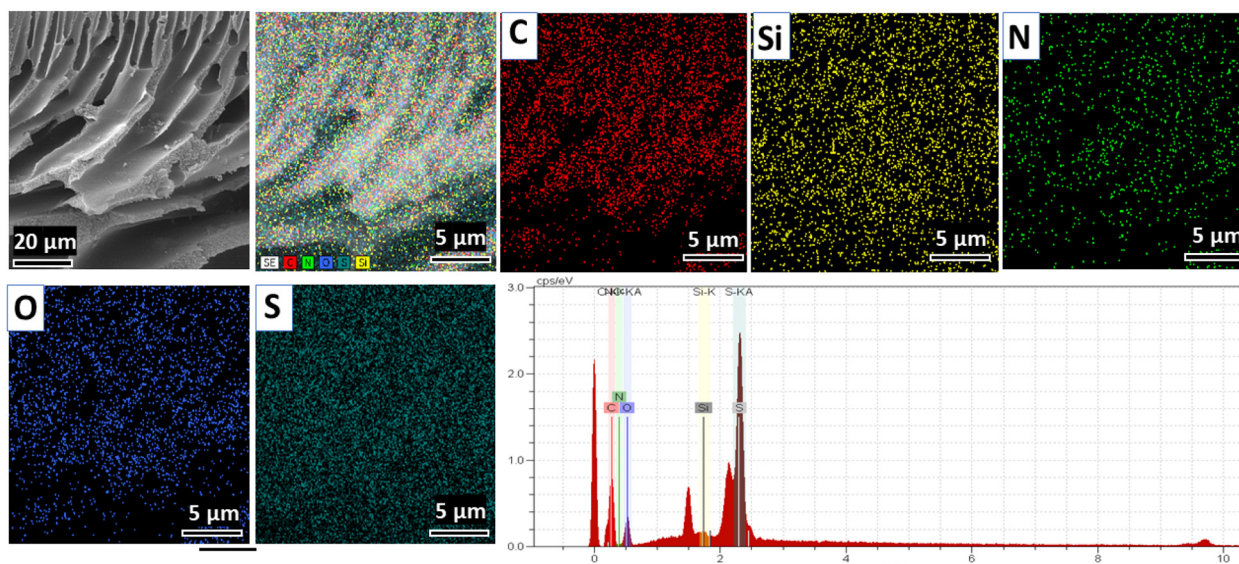


Fig. 10 EDS elemental mapping images of the TFN-GOP_{0.5} membrane.

Table 2 Intrinsic transport parameters of TFC and TFN-FO membranes evaluated under RO mode: water permeability (*A*), salt permeability (*B*), salt rejection (*R*), selectivity ratio (*B/A*), and structural parameter (*S*)

FO membranes	<i>A</i> (LMH per bar)	<i>R</i> (%)	<i>B</i> (LMH)	<i>B/A</i> (bar)	<i>S</i> (μm)
TFC	1.22 ± 0.06	94.4 ± 0.6	0.30 ± 0.04	0.25 ± 0.03	579 ± 40
TFN-GO _{0.5}	1.63 ± 0.10	93.8 ± 0.35	0.45 ± 0.03	0.27 ± 0.015	442 ± 73
TFN-GOP _{0.25}	1.97 ± 0.1	95.1 ± 0.3	0.42 ± 0.05	0.21 ± 0.015	385 ± 29
TFN-GOP _{0.5}	2.53 ± 0.09	96.3 ± 0.45	0.41 ± 0.07	0.16 ± 0.02	270 ± 26
TFN-GOP ₁	2.47 ± 0.18	91.03 ± 0.61	1.04 ± 0.15	0.42 ± 0.03	350 ± 42

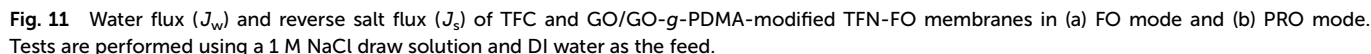
These parameters are measured for each membrane and are summarized in Table 2. Both GO and GO-*g*-PDMA-modified TFN-FO membranes demonstrate higher *A* values than the unmodified TFC membrane, indicating enhanced water permeability. In particular, increasing the GO-*g*-PDMA content led to a notable increase in *A* value, which corresponds with the formation of a rougher PA active layer, as confirmed by SEM and AFM analyses. A rougher PA surface increases the effective contact area with water, thereby improving water permeability. The *R* values vary with the type and concentration of the nanofiller. The TFN-GO_{0.5} membrane exhibits a slightly reduced *R* value (93.8 ± 0.35%) compared to the TFC membrane (94.4 ± 0.6%). In contrast, the TFN-GOP_{0.5} membrane shows an improved *R* value, attributed to a uniform, well-formed PA rejection layer resulting from optimal nanofiller distribution. However, further increasing the GO-*g*-PDMA content to 1.0 wt% (TFN-GOP₁) results in a reduced *R* value (91.03 ± 0.61%), likely due to defective PA layer formation caused by nanofiller aggregation at higher concentrations. The salt per-

meability coefficient (*B*), calculated from *A* and *R* values, followed a similar trend, initially decreasing with moderate GO-*g*-PDMA content and increasing at higher loading levels. These trends in *A*, *B*, and *R* values highlight the role of GO-*g*-PDMA in improving water permeability and selectivity when uniformly dispersed but in causing performance deterioration at high loading. The *S* value, which characterizes the ICP effect, is also evaluated using data from RO and FO tests. A lower *S* value indicates diminished ICP and improved FO flux.^{55,56} The unmodified TFC membrane exhibited the highest *S* value (579 ± 40 μm) and the lowest FO flux. In contrast, TFN-GOP_{0.5} shows the lowest *S* value (270 ± 26 μm), corresponding to the highest FO flux. These results suggest that the addition of GO-*g*-PDMA nanosheets effectively reduces the ICP effect, improving overall FO membrane performance.

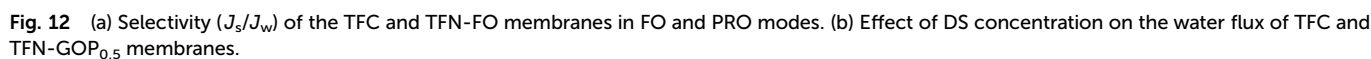
3.5. FO performance

The FO performance of the TFC and GO-*g*-PDMA-modified TFN membranes was evaluated using a cross-flow permeation cell under both FO and PRO modes. The results, including water flux (*J_w*), reverse salt flux (*J_s*), and specific reverse salt flux (*J_s/J_w*), are shown in Fig. 11. The unmodified TFC membrane exhibited *J_w* values of 13.12 ± 0.82 LMH and 21.55 ± 1.2 LMH under FO and PRO modes, respectively. The incorporation of GO-*g*-PDMA nanosheets into the PES substrate led to a marked enhancement in water flux with increasing nanofiller content from 0.25 to 0.5 wt%. For instance, the *J_w* values for the TFN-GO_{0.5}, TFN-GOP_{0.25}, and TFN-GOP_{0.5} membranes increased to 17.3 ± 1.45/31.09 ± 1.2 LMH, 20.27 ± 0.83/38.58 ± 1.3 LMH, and 27.82 ± 1.96/52.1 ± 1.4 LMH under FO/PRO modes, respectively. This enhancement in FO performance is primarily attributed to the introduction of hydrophilic GO-*g*-PDMA nanosheets into the membrane matrix. These nanofillers improve the substrate's average pore size and overall poro-





To evaluate the FO performance of the optimal TFN-GOP_{0.5} membrane, the influence of varying DS concentrations (0.5, 1.0, 1.5, and 2.0 M NaCl) on water flux is investigated and compared with the unmodified TFC membrane, as shown in Fig. 12(b). In both membranes, J_w increases with increasing DS concentration, attributable to the corresponding increase in osmotic pressure, which drives water transport in the FO process.⁶⁰ However, the TFN-GOP_{0.5} membrane shows a much sharper increase in J_w compared to the unmodified TFC mem-



To give a clearer view of how GO-g-PDMA nanosheets affect the membrane substrate, a comparison table (Table 3) has been prepared. This table compares the osmotic performance para-

meters of the FO membranes developed in this study (TFC and TFN-GOP_{0.5}) with those reported for other GO-based FO membranes in the literature. Additionally, the percentage improvement in J_w relative to the unmodified TFC membrane is shown to quantify the performance enhancement. Among the membranes evaluated, the TFN-GOP_{0.5} membrane demonstrates the most favorable combination of high water flux, low reverse salt flux, and superior selectivity, highlighting its competitiveness and optimal design relative to other GO-modified FO membranes.

4. Conclusion

This study demonstrates the development and optimization of a high-performance TFN-FO membrane incorporating GO-g-PDMA nanosheets. The functionalization of GO with PDMA *via* click chemistry is confirmed using FTIR, XRD, TGA, SEM, and EDS analyses. Embedding GO-g-PDMA into the PES substrate significantly enhances its structural and physicochemical properties. At an optimal loading of 0.5 wt%, the modified substrate exhibits increased porosity ($82.6 \pm 1.1\%$), improved hydrophilicity (WCA: $63.2 \pm 0.86^\circ$), and elevated pure water permeability (204.1 ± 5.2 LMH per bar). These enhancements are attributed to the synergistic effects of uniform nanofiller dispersion, greater surface wettability, and the formation of an optimized finger-like pore structure. These improvements effectively reduced ICP, as shown by the lower structural parameter ($S = 270 \pm 26 \mu\text{m}$) of the TFN-GOP_{0.5} membrane, thus enhancing overall FO performance. The interfacial polymerization on the modified substrate formed a PA active layer with increased surface roughness ($R_a = 83.5 \pm 11.3 \text{ nm}$) and thickness ($541.5 \pm 53 \text{ nm}$), which enhanced the effective surface area for water transport while maintaining high salt rejection. In FO and PRO modes, the TFN-GOP_{0.5} membrane achieves water fluxes of 27.82 ± 1.96 LMH and 52.1 ± 1.4 LMH, respectively, using a 1.0 M NaCl draw solution, representing a 124% and 100% increase, respectively, over the unmodified TFC membrane. Notably, the TFN-GOP_{0.5} membrane also exhibits superior selectivity (low J_s/J_w ratio), outperforming other GO-based FO membranes reported in the literature. However, excessive loading of GO-g-PDMA (1.0 wt%) led to nanofiller aggregation, reduced porosity, and compromised PA layer formation, highlighting the critical importance of optimizing nanofiller concentration. Overall, incorporating GO-g-PDMA nanosheets offers a promising strategy to simultaneously address ICP limitations and enhance both water permeability and membrane selectivity.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data supporting the findings of this study are included in the article.

No additional datasets, software, or code were generated or analyzed during this study.

Acknowledgements

This research was funded by the German Federal Ministry of Science and Education in the framework of the MEWAC program under the HydroDeSal project (Project Code 02WME1613).

References

- 1 G. O. R. e Silva, C. R. dos Santos, G. S. Casella, G. P. Drumond and M. C. S. Amaral, Membrane fouling in integrated forward osmosis and membrane distillation systems—a review, *Sep. Purif. Technol.*, 2025, **356**, 129955, DOI: [10.1016/j.seppur.2024.129955](https://doi.org/10.1016/j.seppur.2024.129955).
- 2 M. Elimelech and W. A. Phillip, The future of seawater desalination: Energy, technology, and the environment, *Science*, 2011, **333**, 712–717, DOI: [10.1126/SCIENCE.1200488](https://doi.org/10.1126/SCIENCE.1200488).
- 3 W. Xu, Q. Chen and Q. Ge, Recent advances in forward osmosis (FO) membrane: Chemical modifications on membranes for FO processes, *Desalination*, 2017, **419**, 101–116, DOI: [10.1016/J.DESAL.2017.06.007](https://doi.org/10.1016/J.DESAL.2017.06.007).
- 4 M. Joafshan, A. Shakeri, S. R. Razavi and H. Salehi, Gas responsive magnetic nanoparticle as novel draw agent for removal of Rhodamine B via forward osmosis: High water flux and easy regeneration, *Sep. Purif. Technol.*, 2022, **282**, 119998, DOI: [10.1016/J.SEPPUR.2021.119998](https://doi.org/10.1016/J.SEPPUR.2021.119998).
- 5 A. Shakeri, S. M. M. Babaheydari, H. Salehi and S. R. Razavi, Reduction of the Structure Parameter of Forward Osmosis Membranes by Using Sodium Bicarbonate as Pore-Forming Agent, *Langmuir*, 2021, **37**(24), 7591–7599, DOI: [10.1021/acs.langmuir.1c01097](https://doi.org/10.1021/acs.langmuir.1c01097).
- 6 V. Sant'Anna, L. D. F. Marczak and I. C. Tessaro, Membrane concentration of liquid foods by forward osmosis: Process and quality view, *J. Food Eng.*, 2012, **111**, 483–489, DOI: [10.1016/J.FOODENG.2012.01.032](https://doi.org/10.1016/J.FOODENG.2012.01.032).
- 7 Q. She, Y. K. W. Wong, S. Zhao and C. Y. Tang, Organic fouling in pressure retarded osmosis: Experiments, mechanisms and implications, *J. Membr. Sci.*, 2013, **428**, 181–189, DOI: [10.1016/J.MEMSCI.2012.10.045](https://doi.org/10.1016/J.MEMSCI.2012.10.045).
- 8 X. Zhang, S. Xiong, C. X. Liu, L. Shen, C. Ding, C. Y. Guan and Y. Wang, Confining migration of amine monomer during interfacial polymerization for constructing thin-film composite forward osmosis membrane with low fouling propensity, *Chem. Eng. Sci.*, 2019, **207**, 54–68, DOI: [10.1016/J.CES.2019.06.010](https://doi.org/10.1016/J.CES.2019.06.010).
- 9 D. Li, Y. Yan and H. Wang, Recent advances in polymer and polymer composite membranes for reverse and forward osmosis processes, *Prog. Polym. Sci.*, 2016, **61**, 104–155, DOI: [10.1016/J.PROGPOLYMSCI.2016.03.003](https://doi.org/10.1016/J.PROGPOLYMSCI.2016.03.003).



- 10 H. Jain, A. Kumar, V. D. Rajput, T. Minkina, A. K. Verma, S. Wadhwa, R. Dhupper, M. C. Garg and H. Joshi, Fabrication and characterization of high-performance forward-osmosis membrane by introducing manganese oxide incited graphene quantum dots, *J. Environ. Manage.*, 2022, **305**, 114335, DOI: [10.1016/j.jenvman.2021.114335](https://doi.org/10.1016/j.jenvman.2021.114335).
- 11 P. Oymaci, K. Nijmeijer and Z. Borneman, Development of Polydopamine Forward Osmosis Membranes with Low Reverse Salt Flux, *Membranes*, 2020, **10**, 94, DOI: [10.3390/MEMBRANES10050094](https://doi.org/10.3390/MEMBRANES10050094).
- 12 H. Salehi, M. Rastgar and A. Shakeri, Anti-fouling and high water permeable forward osmosis membrane fabricated via layer by layer assembly of chitosan/graphene oxide, *Appl. Surf. Sci.*, 2017, **413**, 99–108, DOI: [10.1016/j.apsusc.2017.03.271](https://doi.org/10.1016/j.apsusc.2017.03.271).
- 13 M. Li, V. Karanikola, X. Zhang, L. Wang and M. Elimelech, A Self-Standing, Support-Free Membrane for Forward Osmosis with No Internal Concentration Polarization, *Environ. Sci. Technol. Lett.*, 2018, **5**, 266–271, DOI: [10.1021/ACS.ESTLETT.8B00117](https://doi.org/10.1021/ACS.ESTLETT.8B00117).
- 14 L. Shen, W. S. Hung, J. Zuo, L. Tian, M. Yi, C. Ding and Y. Wang, Effect of ultrasonication parameters on forward osmosis performance of thin film composite polyamide membranes prepared with ultrasound-assisted interfacial polymerization, *J. Membr. Sci.*, 2020, **599**, 117834, DOI: [10.1016/j.memsci.2020.117834](https://doi.org/10.1016/j.memsci.2020.117834).
- 15 G. Han, S. Zhang, X. Li, N. Widjojo and T. S. Chung, Thin film composite forward osmosis membranes based on polydopamine modified polysulfone substrates with enhancements in both water flux and salt rejection, *Chem. Eng. Sci.*, 2012, **80**, 219–231, DOI: [10.1016/j.ces.2012.05.033](https://doi.org/10.1016/j.ces.2012.05.033).
- 16 D. L. Shaffer, J. R. Werber, H. Jaramillo, S. Lin and M. Elimelech, Forward osmosis: Where are we now?, *Desalination*, 2015, **356**, 271–284, DOI: [10.1016/j.desal.2014.10.031](https://doi.org/10.1016/j.desal.2014.10.031).
- 17 J. Zhou, H. L. He, F. Sun, Y. Su, H. Y. Yu and J. S. Gu, Structural parameters reduction in polyamide forward osmosis membranes via click modification of the polysulfone support, *Colloids Surf., A*, 2020, **585**, 124082, DOI: [10.1016/j.colsurfa.2019.124082](https://doi.org/10.1016/j.colsurfa.2019.124082).
- 18 P. Lu, W. Li, S. Yang, Y. Wei, Z. Zhang and Y. Li, Layered double hydroxides (LDHs) as novel macropore-templates: The importance of porous structures for forward osmosis desalination, *J. Membr. Sci.*, 2019, **585**, 175–183, DOI: [10.1016/j.memsci.2019.05.045](https://doi.org/10.1016/j.memsci.2019.05.045).
- 19 K. Zheng, S. Zhou and X. Zhou, High-performance thin-film composite forward osmosis membrane fabricated on low-cost PVB/PVC substrate, *RSC Adv.*, 2018, **42**(16), 13382–13392, DOI: [10.1039/C8NJ01677A](https://doi.org/10.1039/C8NJ01677A).
- 20 P. R. Gulave and S. Y. Guhe, An overview of recent advances in inorganic nanomaterials and MOFs in modification of Forward osmosis membranes for Industrial Wastewater Treatment, *J. Inorg. Organomet. Polym. Mater.*, 2025, **35**, 1453–1474, DOI: [10.1007/s10904-024-03353-4](https://doi.org/10.1007/s10904-024-03353-4).
- 21 P. Lu, S. Liang, T. Zhou, T. Xue, X. Mei and Q. Wang, Layered double hydroxide nanoparticle modified forward osmosis membranes via polydopamine immobilization with significantly enhanced chlorine and fouling resistance, *Desalination*, 2017, **421**, 99–109, DOI: [10.1016/j.desal.2017.04.030](https://doi.org/10.1016/j.desal.2017.04.030).
- 22 M. Rastgar, A. Shakeri, A. Bozorg, H. Salehi and V. Saadattalab, Impact of nanoparticles surface characteristics on pore structure and performance of forward osmosis membranes, *Desalination*, 2017, **421**, 179–189, DOI: [10.1016/j.desal.2017.01.040](https://doi.org/10.1016/j.desal.2017.01.040).
- 23 M. J. Park, S. Phuntsho, T. He, G. M. Nisola, L. D. Tijging, X. M. Li, G. Chen, W. J. Chung and H. K. Shon, Graphene oxide incorporated polysulfone substrate for the fabrication of flat-sheet thin-film composite forward osmosis membranes, *J. Membr. Sci.*, 2015, **493**, 496–507, DOI: [10.1016/j.memsci.2015.06.053](https://doi.org/10.1016/j.memsci.2015.06.053).
- 24 M. N. Li, X. J. Chen, Z. H. Wan and S. G. Wang, Forward osmosis membranes for high-efficiency desalination with Nano-MoS₂ composite substrates, *Chemosphere*, 2021, **278**, 130341, DOI: [10.1016/j.chemosphere.2021.130341](https://doi.org/10.1016/j.chemosphere.2021.130341).
- 25 H. Salehi, A. Shakeri and S. R. Razavi, Polyethersulfone–Quaternary Graphene Oxide–Sulfonated Polyethersulfone as a High-Performance Forward Osmosis Membrane Support Layer, *ACS ES&T Water*, 2022, **2**(4), 508–517, DOI: [10.1021/acsestwater.1c00249](https://doi.org/10.1021/acsestwater.1c00249).
- 26 Y. Wang, R. Ou, Q. Ge, H. Wang and T. Xu, Preparation of polyethersulfone/carbon nanotube substrate for high-performance forward osmosis membrane., *Desalination*, 2013, **330**, 70–78, DOI: [10.1016/j.desal.2013.09.028](https://doi.org/10.1016/j.desal.2013.09.028).
- 27 D. Ma, G. Han, S. B. Peh and S. B. Chen, Water-stable metal–organic framework UiO-66 for performance enhancement of forward osmosis membranes, *Ind. Eng. Chem. Res.*, 2017, **56**(44), 12773–12782, DOI: [10.1021/acs.iecr.7b03278](https://doi.org/10.1021/acs.iecr.7b03278).
- 28 R. Ramezani Darabi, M. Peyravi and M. Jahanshahi, Modified forward osmosis membranes by two amino-functionalized ZnO nanoparticles: A comparative study, *Chem. Eng. Res. Des.*, 2019, **145**, 85–98, DOI: [10.1016/j.cherd.2019.02.019](https://doi.org/10.1016/j.cherd.2019.02.019).
- 29 Y. Li, G. He, S. Wang, S. Yu, F. Pan, H. Wu and Z. Jiang, Recent advances in the fabrication of advanced composite membranes, *J. Mater. Chem. A*, 2013, **1**, 10058–10077, DOI: [10.1039/C3TA01652H](https://doi.org/10.1039/C3TA01652H).
- 30 S. F. Chua, K. M. Lam, A. Nouri, E. Mahmoudi, W. L. Ang, W. J. Lau and A. W. Mohammad, Effect of poly(2-(dimethyl-amino)ethyl methacrylate) brush-grafted graphene oxide on polyamide layer formation and nanofiltration performance, *J. Environ. Chem. Eng.*, 2024, **12**, 111935, DOI: [10.1016/j.jece.2024.111935](https://doi.org/10.1016/j.jece.2024.111935).
- 31 S. R. Razavi, A. Shakeri and H. Mahdavi, Polymer-grafted graphene oxide as a high-performance nanofiller for modification of forward osmosis membrane substrates, *ACS. Appl. Polym. Mater.*, 2022, **4**(12), 8878–8891, DOI: [10.1021/acsaapm.2c01266](https://doi.org/10.1021/acsaapm.2c01266).

- Open Access Article. Published on 06 skábmánnu 2025. Downloaded on 2026-05-16 12:29:04.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.



- with different hydrophilic sub layers, *Desalination*, 2012, **284**, 32–41, DOI: [10.1016/J.DESAL.2011.08.034](https://doi.org/10.1016/J.DESAL.2011.08.034).
- 55 K. Zheng, S. Zhou, Z. Cheng and G. Huang, Polyvinyl chloride/quaternized poly phenylene oxide substrates supported thin-film composite membranes: Enhancement of forward osmosis performance, *J. Membr. Sci.*, 2021, **623**, 119070, DOI: [10.1016/J.MEMSCI.2021.119070](https://doi.org/10.1016/J.MEMSCI.2021.119070).
- 56 S. Zhao, N. Sun, P. Dou, S. Lin and T. He, Structure parameter as an intrinsic property of thin-film composite forward osmosis membrane, *Desalination*, 2024, **581**, 117616, DOI: [10.1016/j.desal.2024.117616](https://doi.org/10.1016/j.desal.2024.117616).
- 57 L. Huang, J. T. Arena and J. R. McCutcheon, Surface modified PVDF nanofiber supported thin film composite membranes for forward osmosis, *J. Membr. Sci.*, 2016, **499**, 352–360, DOI: [10.1016/J.MEMSCI.2015.10.030](https://doi.org/10.1016/J.MEMSCI.2015.10.030).
- 58 J. Li, Q. Liu, X. Li, Y. Liu and J. Xie, Template-Assisted Fabrication of Thin-Film Composite Forward-Osmosis Membrane with Controllable Internal Concentration Polarization, *Ind. Eng. Chem. Res.*, 2016, **55**, 5327–5334, DOI: [10.1021/ACS.IECR.6B00874/SUPPL_FILE/IE6B00874_SI_001.PDF](https://doi.org/10.1021/ACS.IECR.6B00874/SUPPL_FILE/IE6B00874_SI_001.PDF).
- 59 A. Arjmandi, M. Peyravi and A. Altaee, Exploring the use of cheap natural raw materials to reduce the internal concentration polarization in thin-film composite forward osmosis membranes, *Chem. Eng. J.*, 2020, **398**, 125483, DOI: [10.1016/j.cej.2020.125483](https://doi.org/10.1016/j.cej.2020.125483).
- 60 A. Hosseinzadeh, A. Altaee, I. Ibrar and J. L. Zhou, Modeling and optimization of reverse salt diffusion and water flux in forward osmosis by response surface methodology and artificial neural network, *Chemical Engineering and Processing-Process Intensification*, 2025, **208**, 110140, DOI: [10.1016/j.cep.2024.110140](https://doi.org/10.1016/j.cep.2024.110140).
- 61 Y. Wang, R. Ou, H. Wang and T. Xu, Graphene oxide modified graphitic carbon nitride as a modifier for thin film composite forward osmosis membrane, *J. Membr. Sci.*, 2015, **475**, 281–289, DOI: [10.1016/J.MEMSCI.2014.10.028](https://doi.org/10.1016/J.MEMSCI.2014.10.028).
- 62 P. Lu, S. Liang, T. Zhou, X. Mei, Y. Zhang, C. Zhang, A. Umar and Q. Wang, Layered double hydroxide/graphene oxide hybrid incorporated polysulfone substrate for thin-film nanocomposite forward osmosis membranes, *RSC Adv.*, 2016, **6**, 56599–56609, DOI: [10.1039/C6RA10080E](https://doi.org/10.1039/C6RA10080E).