

Fabrication and modification of Nanofiltration Membranes Based on Silver/Copper Ferrite Nanocomposites and Their Application in Salt and Heavy Metal Removal

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ABSTRACT

Polyethersulfone (PES)-based nanofiltration membranes were fabricated by incorporating $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles (CNPs) to enhance permeability, hydrophilicity, and antifouling performance. The $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles (CNPs) were synthesized via an environmentally benign co-precipitation route using arginine as a natural reducing agent. The chemical structure and surface functional groups of the synthesized nanoparticles were explicitly characterized by attenuated total reflectance–Fourier transform infrared spectroscopy (ATR-FTIR). In contrast, their surface morphology, particle distribution, and elemental homogeneity were examined using field-emission scanning electron microscopy (FESEM) coupled with energy-dispersive X-ray spectroscopy (EDS). Similarly, the successful incorporation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles into the polymeric membrane matrix was confirmed by ATR-FTIR analysis, which revealed the emergence of new characteristic absorption bands associated with interfacial interactions between the nanoparticles and the polymer chains. The surface morphology and spatial distribution of the embedded nanoparticles within the membrane were further investigated using FESEM, confirming a uniformly modified membrane surface without noticeable agglomeration. Mixed matrix membranes were prepared by the phase inversion technique at various CNPs loadings (0.001–1.0 wt%), and their physicochemical properties were systematically evaluated. The addition of $\text{CuFe}_2\text{O}_4/\text{Ag}$ CNPs significantly reduced the water contact angle from 70° to 45° and increased membrane porosity from 75% to 89%, improving surface hydrophilicity and pore interconnectivity. The optimized membrane (0.1 wt%) exhibited a 2.5-fold increase in pure-water flux (from 12 to $29.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and achieved 94% Na_2SO_4 rejection. Moreover, it demonstrated excellent heavy-metal ion removal efficiencies, with 93% and 81% rejection for Cu(II) and Cr(II) , respectively. The flux recovery ratio (FRR) markedly improved from 61% for pristine PES to 88% for the modified membrane, indicating enhanced antifouling resistance. These improvements are attributed to the synergistic effects of the hydrophilic $\text{CuFe}_2\text{O}_4/\text{Ag}$ CNPs, which enhanced charge selectivity and pore uniformity. Overall, the $\text{CuFe}_2\text{O}_4/\text{Ag}$ -PES nanocomposite membranes exhibited superior water flux, ion selectivity, and fouling resistance, demonstrating strong potential for sustainable wastewater treatment and desalination applications.

KEYWORDS: Nanofiltration; $\text{CuFe}_2\text{O}_4/\text{Ag}$ hybrid nanoparticles; PES mixed matrix membrane; Heavy metal removal; Antifouling performance.

1. Introduction

Membrane-based separation technologies are widely recognized as efficient and sustainable approaches for advanced wastewater treatment due to their high selectivity, operational simplicity, modular configuration, and relatively low energy requirements.

Both inorganic and polymeric membranes have been extensively investigated, each presenting specific advantages and limitations [1]. Although inorganic membranes offer superior thermal and chemical stability, their brittleness and high fabrication costs limit large-scale industrial application. Consequently,

polymeric membranes remain dominant in water treatment systems, with polyethersulfone (PES) being one of the most widely utilized materials owing to its mechanical robustness, thermal resistance, and chemical durability [2]. PES membranes offer an advantageous combination of mechanical robustness, thermal resistance, and chemical durability, rendering them suitable for long-term operation under harsh conditions. Nevertheless, the inherently hydrophobic nature of PES promotes the adsorption of organic matter, proteins, and microorganisms, resulting in severe membrane fouling and progressive flux decline. This limitation significantly compromises separation efficiency, operational stability, and membrane lifespan, thereby increasing maintenance frequency and overall treatment costs [3]. Improving the hydrophilicity and antifouling performance of PES membranes therefore remains a critical research objective. To address these challenges, various modification strategies have been developed, including surface grafting, coating, polymer blending, and incorporation of functional nanomaterials. Among these, mixed-matrix membranes (MMMs) have attracted significant attention because they enable the integration of polymer processability with the functional advantages of inorganic nanofillers [4, 5]. Incorporation of suitable nanoparticles into the PES matrix has been shown to enhance hydrophilicity, mechanical strength, antifouling properties, and, in some cases, catalytic or antibacterial activity, thereby improving membrane durability and separation performance [6]. Recent studies demonstrate that ferrite-based, magnetic, MXene-derived, and carbon-based nanomaterials are particularly effective in tailoring membrane characteristics. For instance, CuFe_2O_4 -containing PES membranes have shown improved surface hydrophilicity and antifouling behavior [7, 8], while CoFe_2O_4 -modified membranes exhibited enhanced contaminant rejection and structural stability [9]. Magnetic nanocomposites such as Fe_3O_4 @MXene have demonstrated strong adsorption capability toward heavy metal ions [10], and carbon-based composite membranes have achieved enhanced ion removal and pore structure optimization [11]. These findings collectively highlight the potential of functional nanofillers in enhancing separation efficiency and mitigating fouling in polymeric membrane systems. Among ferrite materials, copper ferrite (CuFe_2O_4) is particularly attractive due to its stable spinel structure, magnetic properties, favorable electrical conductivity, and

catalytic activity. Its relatively narrow band gap and high surface area contribute to effective degradation of organic pollutants and adsorption of heavy metals [12]. Silver nanoparticles (AgNPs), known for their strong antimicrobial activity and excellent electron transfer characteristics, can further enhance membrane functionality. The integration of CuFe_2O_4 with Ag to form $\text{CuFe}_2\text{O}_4/\text{Ag}$ hybrid nanoparticles is expected to generate synergistic effects that improve catalytic, antibacterial, and adsorptive performance [13]. Despite these advances, systematic investigation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ hybrid nanoparticle incorporation into PES nanofiltration membranes remains limited, particularly regarding the influence of nanoparticle loading on membrane morphology, surface characteristics, separation efficiency, and antifouling behavior. Therefore, in this study, $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles were synthesized via chemical co-precipitation and incorporated into PES membranes using the phase inversion technique. The structural and surface properties of the resulting nanocomposite membranes were characterized, and their separation and antifouling performance were systematically evaluated. This work aims to develop a multifunctional PES-based nanofiltration membrane with enhanced permeability, stability, and resistance to fouling for sustainable wastewater treatment applications.

2. Experimental

2.1. Material

All reagents were of analytical grade and used without further purification. Polyethersulfone (PES, Ultrason® E6020P, $M_w \approx 58,000 \text{ g}\cdot\text{mol}^{-1}$) was supplied by BASF (USA). N,N-dimethylacetamide (DMAC, $M_w = 87.12 \text{ g}\cdot\text{mol}^{-1}$, density = $0.94 \text{ g}\cdot\text{cm}^{-3}$) was used as the solvent. Polyvinylpyrrolidone (PVP, $M_w \approx 25,000 \text{ g}\cdot\text{mol}^{-1}$) served as a pore-forming additive. Sodium sulfate (Na_2SO_4), copper(II) sulfate (CuSO_4), and chromium(VI) salt (correct species must be specified) were purchased from Merck (Germany). Iron(III) nitrate nonahydrate ($\text{Fe}(\text{NO}_3)_3\cdot 9\text{H}_2\text{O}$, $\geq 98\%$) and copper(II) nitrate trihydrate ($\text{Cu}(\text{NO}_3)_2\cdot 3\text{H}_2\text{O}$, $\geq 99\%$) were used as metal precursors for ferrite synthesis. Sodium hydroxide (NaOH , $\geq 99\%$) was used as precipitating agent. Silver nitrate (AgNO_3) and L-arginine were obtained from Sigma-Aldrich. Deionized water (resistivity $\geq 18 \text{ M}\Omega\cdot\text{cm}$) was used throughout all experiments.

2.2. Synthesis of Copper Ferrite Nanoparticles (CuFe_2O_4)

CuFe_2O_4 nanoparticles were synthesized via a controlled co-precipitation method [14]. $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ were dissolved in deionized water at a molar ratio of Fe:Cu = 2:1 under continuous magnetic stirring at 60 °C for 2 h to ensure complete homogenization. Subsequently, 1 M NaOH solution was added dropwise under vigorous stirring until the pH exceeded 10, promoting the formation of metal hydroxide intermediates. The resulting precipitate was aged at 60 °C for 1 h to improve crystallization. The precipitate was separated by centrifugation (8000 rpm, 10 min), washed repeatedly with deionized water and ethanol until neutral pH was reached, and dried at 90 °C for 8 h. The dried powder was calcined at 600 °C for 3 h (heating rate: 5 °C·min⁻¹) in air to obtain crystalline spinel CuFe_2O_4 nanoparticles. The calcined product was ground and sieved to minimize agglomeration.

2.3. Synthesis of Silver-Decorated Copper Ferrite composite nanoparticle ($\text{CuFe}_2\text{O}_4/\text{Ag}$)

Silver nanoparticles were deposited onto the CuFe_2O_4 surface via in situ chemical reduction using L-arginine as a mild reducing and stabilizing agent. Briefly, 1 g of L-arginine was dissolved in 50 mL of deionized water (20 mg·mL⁻¹). A predetermined amount of AgNO_3 solution was added to achieve a CuFe_2O_4 :Ag molar ratio of 1:2 under continuous stirring. The CuFe_2O_4 suspension was then introduced into the AgNO_3 -arginine solution and maintained at 70 °C for 8 h under constant stirring. During this process, Ag^+ ions were reduced to metallic Ag^0 and nucleated onto the ferrite surface, forming $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles. The product was washed repeatedly with deionized water to remove residual reactants and dried at 60 °C overnight [15].

2.4. Preparation of Mixed Matrix NF-Membranes

Mixed matrix nanofiltration membranes containing the $[\text{CuFe}_2\text{O}_4/\text{Ag}]$ composite nanoparticles were fabricated using the same phase inversion approach. Pre-measured quantities of $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticle were initially dispersed in the solvent (DMAc) under continuous stirring to ensure homogeneous distribution of the nanoparticles. Afterward, 18 wt% PES and 1 wt% PVP were gradually incorporated into the nanoparticle dispersion, and the resulting mixture was stirred for more than 4 hours to obtain a uniform polymeric solution. The solution was left undisturbed for 24 hours at ambient temperature to ensure complete removal of entrapped air. Subsequently, the degassed solution was cast onto a clean glass substrate using a 200 µm film applicator. The cast films were immediately immersed in deionized (DI) water to induce phase inversion and solidify the membrane structure. Finally, the fabricated membranes were soaked in DI water for 24 hours to remove residual solvent and were then stored for further characterization [16]. The composition of the casting solutions is summarized in Table 1.

2.5. Characterization and Analytical Methods

The structural, morphological, and elemental characteristics of the synthesized $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles and the fabricated nanocomposite membranes were systematically analyzed using complementary characterization techniques. The chemical structures of both the composite nanoparticles and membrane samples were examined by attenuated total reflectance–Fourier transform infrared spectroscopy (ATR-FTIR). Spectra were recorded using a Galaxy Series 5000 spectrometer (KBr pellet method) for nanoparticle analysis and an ABB Bomem MB-104 spectrometer (Switzerland) for membrane characterization. Morphological features

Table 1-The formulation of the casting solution for the membrane samples.

Sample	PES (wt%)	PVP (wt%)	DMAc (wt%)	$\text{CuFe}_2\text{O}_4/\text{Ag}$ (wt%)
M_0	18	1	81.000	0.000
M_1	18	1	80.999	0.001
M_2	18	1	80.990	0.010
M_3	18	1	80.900	0.100
M_4	18	1	80.000	1.000

of the composite nanoparticles as well as the surface and cross-sectional structures of the membranes were investigated using field emission scanning electron microscopy (FESEM). Nanoparticle morphology was analyzed using a SU3500 instrument (USA), while membrane morphology was examined using a Tescan Mira III microscope (Czech Republic). For cross-sectional imaging, membrane samples were immersed in liquid nitrogen and subsequently fractured to expose their internal structure.

Elemental mapping analysis was conducted to determine the spatial distribution of constituent elements and to evaluate the homogeneity of nanoparticle dispersion within the polymer matrix.

Surface roughness parameters of the membranes were quantified using a three-dimensional surface profiler, and the obtained data were analyzed with DME-SPM software (version 2.1.1.2).

The overall porosity of both pristine and modified membranes was determined gravimetrically according to Equation (1) [17]:

$$\varepsilon\% = \left(\frac{W_w - W_d}{A \times l \times d_m} \right) \times 100 \quad (1)$$

Where W_w and W_d denote the wet and dry weights of the membrane, respectively; A represents the effective membrane area; d_w is the density of water; and L corresponds to the membrane thickness.

The mean pore radius (r_m) was estimated using the Guerout–Elford–Ferry equation (Equation 2), taking into account the transmembrane pressure (ΔP), volumetric permeate flow rate (Q), and water viscosity ($\eta = 8.9 \times 10^{-4}$ Pa·s) [18].

$$r_m = \sqrt{\frac{(2.9 - 1.75\varepsilon) \times 8\eta L Q}{\varepsilon A \Delta P}} \quad (2)$$

2.7. Permeability, fouling resistance, and separation efficiency of the MMM

The functional performance of the prepared membranes was examined with respect to pure water flux (PWF), permeability to a milk solution, and rejection efficiency for sodium sulfate (Na_2SO_4) and various heavy-metal ion solutions. All filtration experiments were conducted in a dead-end filtration cell with an effective area of 19.6 cm^2 . Before testing, the membranes were compacted by filtering distilled

water at 5 bar for 30 minutes to ensure structural stability. Subsequently, the pressure was adjusted to 4.5 bar for steady-state filtration. During operation, the feed solution was continuously stirred at 500 rpm to minimize concentration polarization effects near the membrane surface. The permeate flux (J_w) was determined using Equation (3) [19]:

$$J = \frac{V}{A \times t} \quad (3)$$

where V is the collected permeate volume (L), A is the membrane surface area (m^2), and Δt represents the filtration time (h).

The feed concentrations used for separation performance evaluation were 1000 ppm Na_2SO_4 , 20 ppm heavy-metal ions, and 250 ppm milk powder solution. The solute rejection efficiency (R) was calculated using Equation (4), adapted from [20]:

$$\% \text{Rejection} = \left(1 - \frac{C_p}{C_f} \right) \times 100 \quad (4)$$

where C_p and C_f correspond to the solute concentrations in the feed and permeate streams, respectively.

To assess antifouling behavior, a three-step filtration protocol was applied, and the flux recovery ratio (FRR) was determined using Equation (5). In the first step, pure water was filtered through the membrane at 0.45 MPa for one hour to record the initial flux (J_{w1}). In the second step, a 250 ppm milk solution was filtered to obtain the fouled-state flux (J_p). In the third step, the fouled membranes were rinsed with distilled water for 20 minutes and subsequently refiltered with pure water for one hour to record the recovered flux (J_{w2}) [16].

$$FRR\% = \left(\frac{J_{w2}}{J_{w1}} \right) \times 100 \quad (5)$$

The fouling parameters—total fouling (R_t), reversible fouling (R_r), and irreversible fouling (R_{ir}) were calculated using Equations (6)–(8) [16]:

$$R_{ir}\% = (1 - FRR) \times 100 \quad (6)$$

$$R_r\% = \left(\frac{J_{w2} - J_p}{J_{w1}} \right) \times 100 \quad (7)$$

Irreversible fouling occurs when firmly adhered or embedded contaminants remain trapped within the membrane pores and cannot be removed through physical cleaning [21].

3. RESULTS AND DISCUSSION

3.1. Synthesized Nanoparticle Characterization

The FTIR spectrum of the synthesized $\text{CuFe}_2\text{O}_4/\text{Ag}$ composite nanoparticles is presented in Figure 1(a). A broad absorption band observed in the range of $3400\text{--}3500\text{ cm}^{-1}$ corresponds to the stretching vibration of surface hydroxyl ($-\text{OH}$) groups, which are typically associated with adsorbed moisture and surface metal-hydroxyl functionalities. Weak bands near 2920 cm^{-1} are attributed to residual C-H stretching vibrations, likely originating from trace organic species involved

during synthesis. A characteristic absorption band centered at approximately $580\text{--}600\text{ cm}^{-1}$ is assigned to metal-oxygen (M-O) lattice vibrations, commonly reported for spinel-type copper ferrite structures [7, 22]. Although FTIR alone cannot conclusively confirm phase purity, the presence of this band, together with the adopted calcination temperature (600°C), which is widely reported to yield crystalline CuFe_2O_4 , supports the successful formation of ferrite-type metal-oxygen networks. The FTIR spectra of pristine and modified membranes (Figure 1(b)) exhibit the characteristic vibrational features of PES. The aromatic C=C stretching bands at ≈ 1580 and $\approx 1480\text{ cm}^{-1}$, as well as the asymmetric and symmetric O=S=O stretching modes at ≈ 1240 and $\approx 1150\text{ cm}^{-1}$, remain unchanged after nanoparticle incorporation, confirming that the chemical backbone of PES

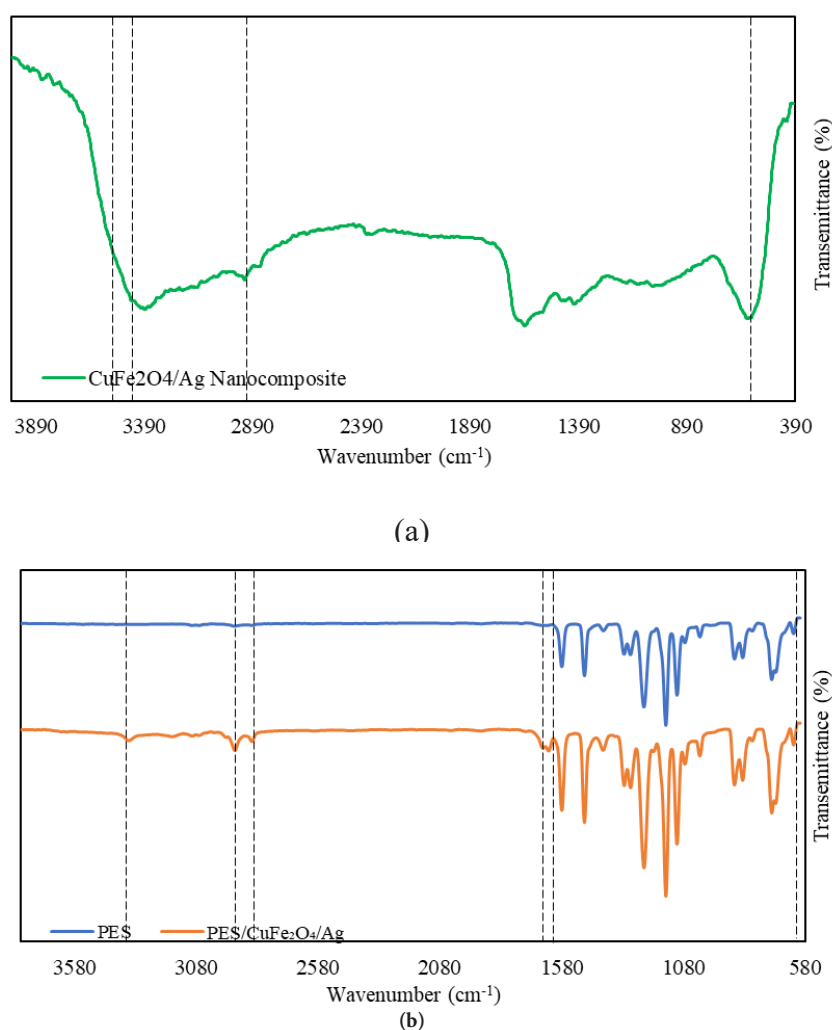


Figure 1. FTIR analysis of (a) the modified composite nanoparticle and (b) the pristine and modified PES membranes.

is preserved. A slight increase in intensity in the 580–600 cm^{-1} region is observed for the modified membranes, consistent with the incorporation of metal–oxygen species within the polymer matrix. Additionally, a subtle narrowing of the broad O–H band suggests possible interfacial interactions, such as hydrogen bonding or dipole interactions, between surface hydroxyl groups of $\text{CuFe}_2\text{O}_4/\text{Ag}$ and the sulfone functionalities of PES. These interactions are beneficial for nanoparticle dispersion stability within the matrix. Overall, the spectroscopic results indicate successful embedding of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles without altering the intrinsic chemical structure of the polymer [7, 22].

3.2. FE-SEM and Elemental Mapping Analysis

FESEM images of the synthesized $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles (Figure 2(a)) reveal nanoscale particles with relatively uniform morphology. No severe agglomeration was observed at the magnification scale employed [22]. The EDX spectrum (Figure 2(b)) confirms the presence of Cu, Fe, Ag, O, and C elements, consistent with the intended composite composition. Elemental mapping (Figure 2(c)) demonstrates a homogeneous spatial distribution of Cu, Fe, and Ag signals, indicating that silver species are dispersed over the ferrite framework rather than forming isolated large clusters. While crystallographic confirmation would require XRD analysis, the combined evidence from FTIR, elemental composition, and synthesis conditions supports the successful preparation of a $\text{CuFe}_2\text{O}_4/\text{Ag}$ hybrid nanocomposite.

3.3 Membrane Characterization

3.3.1 Membrane Morphology

Cross-sectional FESEM images (Figure 3) reveal the typical asymmetric architecture of phase-inverted PES membranes, consisting of a thin dense selective layer supported by a porous sublayer. The pristine membrane (M0) exhibits a relatively compact top layer with limited macrovoid development and a sponge-like substructure. Upon incorporation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles, pronounced morphological changes are observed. At low loading (0.001 wt%, M1), the sublayer becomes more open, indicating accelerated solvent–nonsolvent exchange during phase inversion. The hydrophilic nature of the nanoparticles enhances thermodynamic instability in the casting solution, promoting instantaneous demixing and the formation of larger finger-like pores [23]. At intermediate loadings (0.01–0.1 wt%, M2–

M3), well-developed macrovoids extend across the membrane thickness, and the finger-like structure becomes more elongated and interconnected. This morphology suggests an optimal balance between nanoparticle dispersion and polymer–solvent interaction. The enhanced water affinity of $\text{CuFe}_2\text{O}_4/\text{Ag}$ reduces interfacial tension between the polymer solution and coagulation bath, facilitating rapid mass transfer and pore formation. However, at high loading (1 wt%, M4), the membrane cross-section exhibits a thicker selective layer and partially collapsed macrovoids. This structural densification is attributed to increased casting solution viscosity and possible nanoparticle agglomeration, which retard solvent diffusion and delay phase separation kinetics [22]. The morphological transition from highly porous (M3) to relatively compact (M4) directly correlates with the observed flux and rejection behavior discussed later. Elemental mapping (Figure 4) confirms the distribution of Cu, Fe, and Ag across the membrane matrix, indicating successful nanoparticle incorporation without large-scale phase segregation.

The surface topography of the membranes was analyzed using three-dimensional (3D) imaging, and the roughness parameters, including the arithmetic mean roughness (R_a), are summarized in Table 2. The pristine PES membrane exhibited pronounced peaks and valleys, reflecting the intrinsic heterogeneity generated during phase inversion. Such surface irregularities are typical for hydrophobic polymeric membranes prepared via nonsolvent-induced phase separation. Incorporation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles induced noticeable modifications in surface morphology. A slight increase in R_a was observed for M1, which may be attributed to localized nanoparticle clusters and non-uniform dispersion within the polymer matrix. Among the modified membranes, M2 exhibited the highest roughness value, possibly due to partial nanoparticle aggregation that generated surface protrusions and amplified topographical heterogeneity [22]. Increased surface roughness can enlarge the effective interfacial area between the membrane and feed solution. However, in the absence of dedicated adsorption measurements, its influence on solute retention is considered complementary rather than dominant. At intermediate loading (M3), the surface became comparatively smoother and more uniform. This behavior can be associated with improved nanoparticle dispersion and more homogeneous phase separation kinetics, leading to a balanced distribution of surface

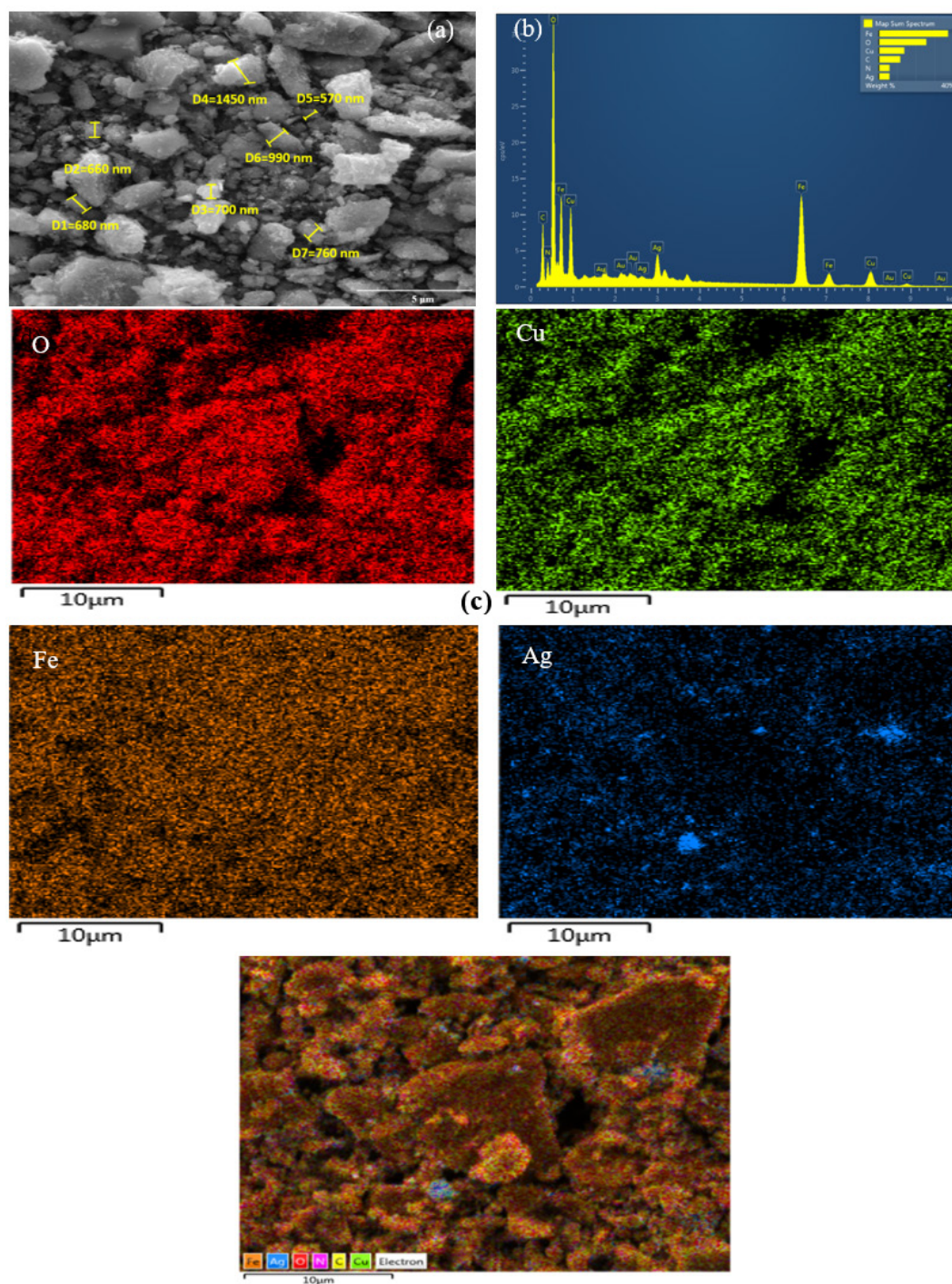


Figure 2. (a) FE-SEM image of the CuFe₂O₄/Ag composite nanoparticle, (b) corresponding EDX spectrum, and (c) elemental mapping images of O, Cu, Fe, and Ag.

features. During phase inversion, hydrophilic additives may preferentially migrate toward the membrane–water interface due to thermodynamic driving forces, contributing to partial leveling of surface asperities [18]. At the highest loading (M4), surface irregularity increased again, likely due to intensified nanoparticle agglomeration and increased casting solution viscosity, which disrupted uniform surface formation. Consequently, the Ra value of M4 slightly exceeded

that of the pristine membrane. The 3D analyses were conducted over a $6\ \mu\text{m} \times 6\ \mu\text{m}$ scanning area using SPM software (version 6.4, Femtoscan), revealing systematic roughness variations consistent with the observed structural and permeability trends.

3.3.2. Surface Hydrophilicity of the Membranes

The static water contact angle measurements (Table 2) demonstrate a progressive decrease from 70° for pristine PES (M0) to 45° for M4. This substantial

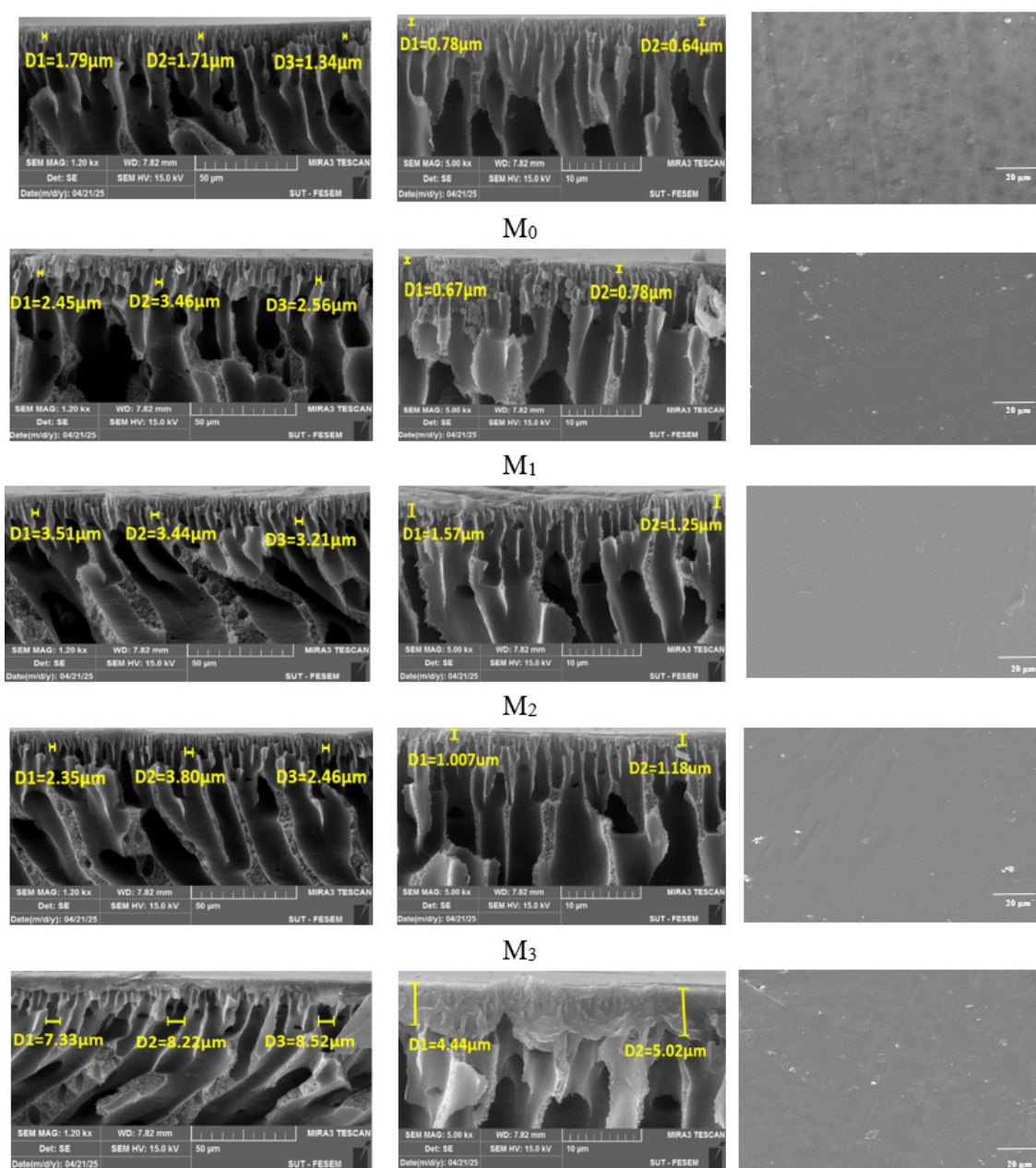


Figure 3. FE-SEM images of the cross-section and surface morphology of all fabricated membranes.

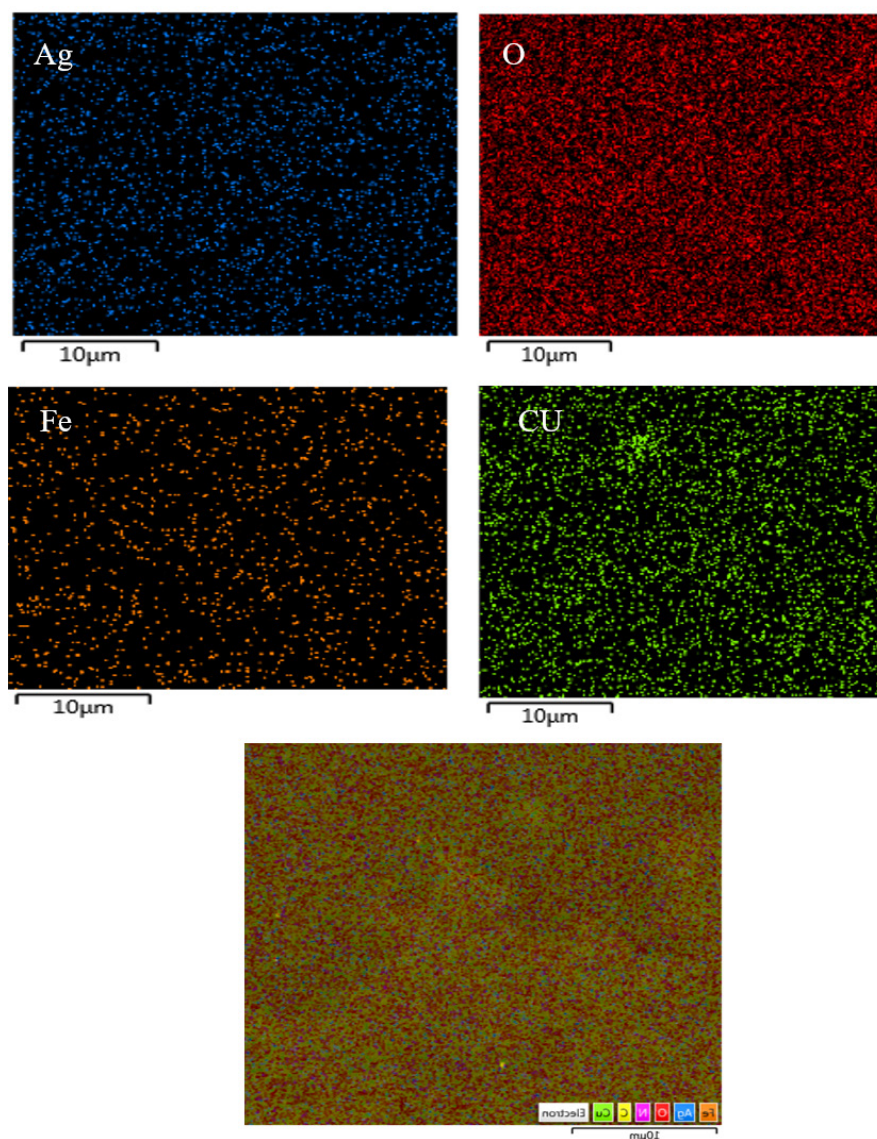


Figure 4. Elemental mapping images of the surface of the modified membrane showing the distribution of O, Cu, Fe, C, and Ag elements.

reduction indicates a significant improvement in surface hydrophilicity following nanoparticle incorporation. The enhancement in wettability can be attributed to surface-exposed hydroxyl and metal–oxygen groups associated with $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles [24]. During phase inversion, hydrophilic species tend to migrate toward the membrane–water interface due to thermodynamic driving forces, resulting in enrichment of polar functional groups at the surface [25]. The increased hydrophilicity promotes the formation of a stable hydration layer via hydrogen bonding with water molecules. This hydrated layer reduces interfacial

resistance to water transport and simultaneously acts as a physical barrier against foulant adsorption. Importantly, the monotonic decrease in contact angle correlates with the increase in pure water flux up to M3, suggesting that surface wettability plays a dominant role in permeability enhancement.

3.3.3. Pore Structure and Porosity

As summarized in Table 2, the mean pore radius increased progressively with increasing $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticle loading, reaching approximately 7.6 nm at 0.1 wt% (M3). This pore enlargement is consistent with accelerated demixing kinetics induced by the addition of hydrophilic nanoparticles [8, 26].

Table 2-Examining Membrane Parameters: Total Porosity, Average Pore Radius, and Roughness Surface Characteristics.

Name	Porosity (%)	Average pore size (nm)	Contact angle (°)	Roughness(nm)
Bare PES	75.2±0.2	2.6±0.2	70±2.2	7.77
M ₁ (CuFe ₂ O ₄ /Ag 0.001 wt%)	79.8±0.1	2.8±0.2	67±0.2	8.51
M ₂ (CuFe ₂ O ₄ /Ag 0.01 wt%)	85.3±0.2	3.1±1.0	56±2.8	8.94
M ₃ (CuFe ₂ O ₄ /Ag 0.11 wt%)	89.9±0.2	3.7±0.1	52±2.1	8.34
M ₄ (CuFe ₂ O ₄ /Ag 1wt%)	80.8±0.1	7.6±0.6	45±2.4	9.65

At higher loading (1 wt%, M₄), the mean pore radius remained comparable; however, the overall porosity decreased to 80.8%, likely due to nanoparticle agglomeration and partial pore obstruction, which restricted solvent–nonsolvent exchange and promoted formation of a denser polymer network [6, 27]. The addition of CuFe₂O₄/Ag nanoparticles also increased membrane porosity relative to the unmodified PES membrane. This enhancement may be attributed to the physicochemical behavior of the nanoparticles at the polymer–water interface. Due to their relatively low density and high surface energy, nanoparticles may migrate toward the interface during phase inversion, facilitating localized solvent–polymer interactions and the formation of interconnected microvoids [28]. At the highest loading (1 wt%, M₄), while the mean pore radius remained comparable to M₃, the overall porosity decreased to 80.8%. This reduction is likely due to nanoparticle agglomeration and partial pore obstruction, which can restrict solvent–nonsolvent exchange and lead to a denser polymer network [29, 30]. Such structural changes highlight that excessive nanoparticle content may compromise the uniformity of the porous architecture despite maintaining large pore dimensions.

Overall, the M₃ membrane represents an optimal balance between pore size, porosity, and structural stability, providing efficient water transport while maintaining mechanical integrity.

3.3.4. Membrane Filtration Performance

The influence of CuFe₂O₄/Ag composite nanoparticle incorporation on the pure water flux (PWF) and salt rejection behavior of the membranes is shown in Figure 5. A notable increase in water permeability was observed upon addition of the hydrophilic CuFe₂O₄/Ag nanoparticles into the PES matrix. The PWF increased from 15.1 L·m⁻²·h⁻¹ for

the pristine PES membrane (M₀) to 29 L·m⁻²·h⁻¹ for the M₃ membrane containing 0.1 wt% CuFe₂O₄/Ag. This enhancement can likely be attributed to two complementary factors. First, the improved surface hydrophilicity, inferred from reduced water contact angles and the presence of hydroxyl and silver–oxygen functionalities, may reduce interfacial resistance and facilitate water transport [31, 32]. Second, morphological and porosity analyses (Figure 3 and Table 2) suggest that incorporation of the nanoparticles leads to a more open and interconnected pore structure, which likely contributes to increased flux [33]. The trend in PWF correlates well with the measured mean pore radius, supporting this interpretation.

At the highest nanoparticle loading (1 wt%, M₄), a slight decrease in PWF was observed. This behavior may result from nanoparticle agglomeration and partial obstruction of pore channels, which could increase local solution viscosity and limit solvent–nonsolvent exchange during phase inversion, thereby producing a denser selective layer. Despite this reduction, all nanoparticle-modified membranes exhibited significantly higher PWF than the unmodified PES membrane, likely due to the combined effects of enhanced surface hydrophilicity and the modified porous architecture [34].

The salt rejection behavior of the membranes was evaluated using Na₂SO₄ as a model electrolyte (Figure 6). The pristine PES membrane (M₀) exhibited a comparatively low rejection of 66%, likely due to its hydrophobic surface and heterogeneous pore structure. Incorporation of CuFe₂O₄/Ag nanoparticles substantially improved the rejection performance, reaching a peak of 94% for the M₃ membrane (0.1 wt% loading). This enhancement may be attributed to the combined effects of increased

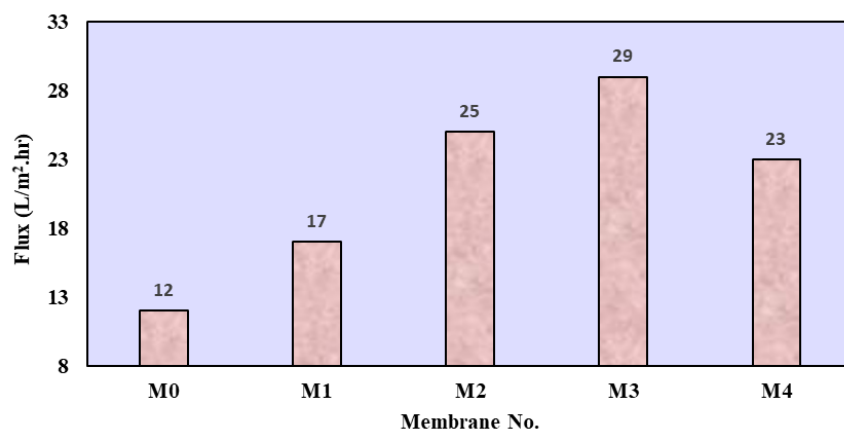


Figure 5. The flux change trend with increasing CuFe₂O₄/Ag nanoparticles.

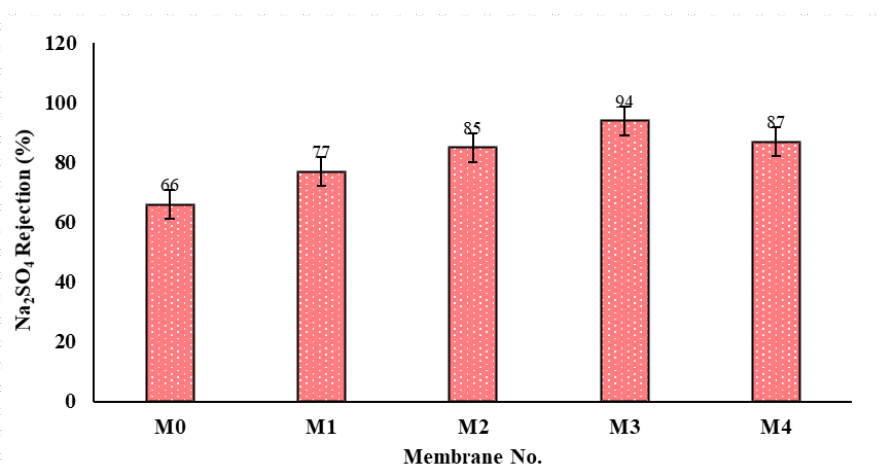


Figure 6. The salt rejection of prepared membranes.

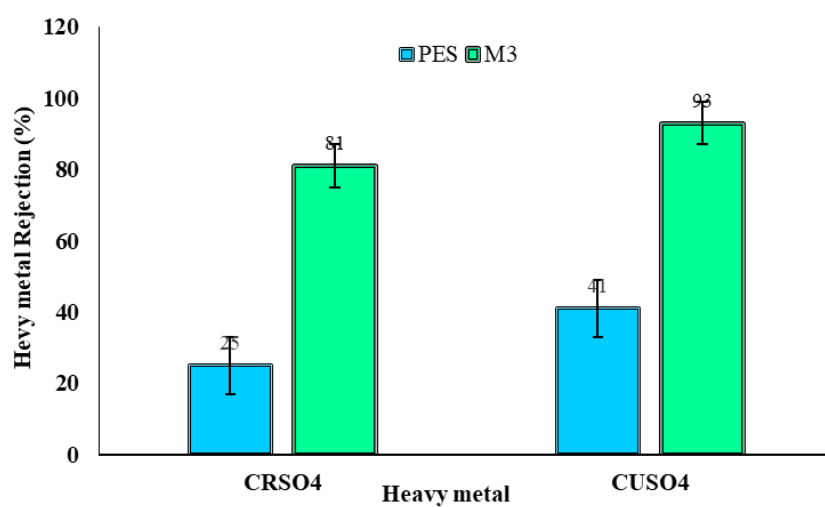


Figure 7. The rejection of CrSO₄ and CuSO₄ for M0 and M3.

surface hydrophilicity, improved pore uniformity, and possible electrostatic interactions associated with the presence of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles. Specifically:

1. Enhanced hydrophilicity, inferred from contact angle measurements, likely improves wettability and reduces concentration polarization at the membrane–solution interface, maintaining higher rejection efficiency [35, 36].

2. Uniform distribution of nanoparticles may promote more consistent pore architecture and provide additional adsorption sites, which could facilitate selective ion transport [37].

3. At higher loading (1 wt%, M4), a slight reduction in rejection was observed, likely due to nanoparticle agglomeration and partial pore obstruction, which may create non-uniform pathways for ion transport [37, 38].

Overall, the M3 membrane exhibits the most favorable balance between permeability and salt rejection, likely resulting from the combination of optimized pore structure, surface hydrophilicity, and homogeneous dispersion of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles within the polymer matrix [39].

The separation efficiency of heavy metal ions was evaluated using the optimized $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanocomposite membrane (M3) and the pristine PES membrane (M0), with chromium sulfate (CrSO_4) and copper sulfate (CuSO_4) as representative feed solutions [40]. At the optimal nanoparticle loading of 0.1 wt%, the M3 membrane demonstrated significantly improved heavy metal rejection compared with the unmodified membrane (Figure 7). Specifically, Cr^{2+} rejection increased from 25% for M0 to 81% for M3, while Cu^{2+} rejection rose from 41% to 93%. This

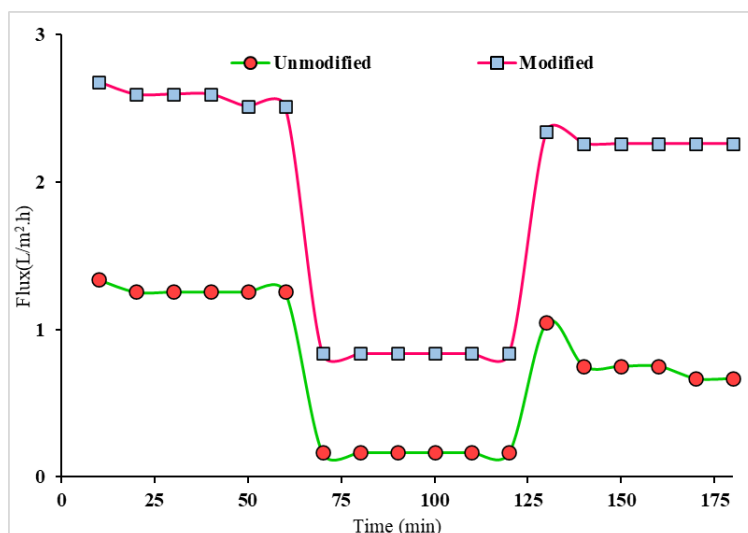


Figure 8. The j_{w1} , j_p and j_{w2} of virgin membrane M0 and M3 as optimum membrane.

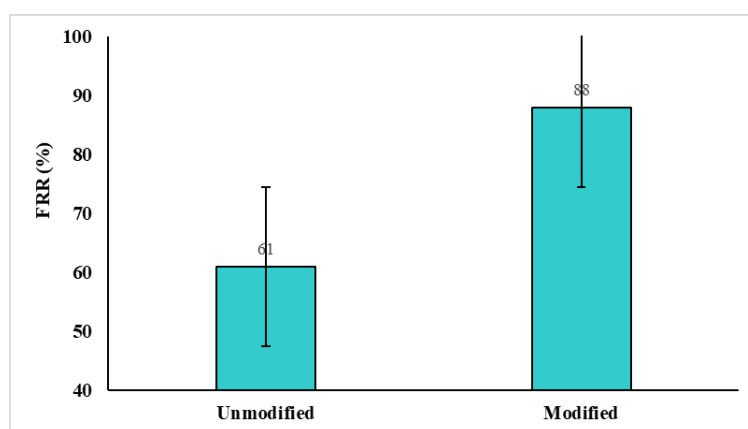


Figure 9. The FRR Parameter for M0 and M3.

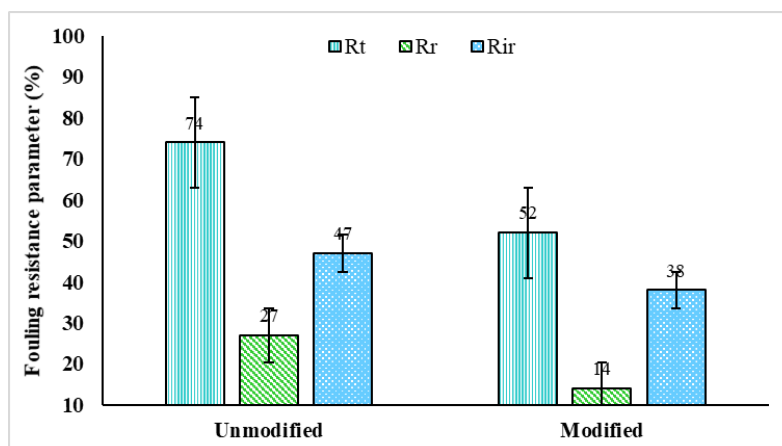


Figure 10. The values of fouling factors for modified M3 and unmodified M0 membranes

enhancement may be attributed to the combined effects of increased surface hydrophilicity, more uniform pore structure, and additional adsorption sites provided by the homogeneously dispersed $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles [41]. FESEM analyses (Figure 2) indicate improved pore uniformity and roughness in the modified membranes, which likely contribute to the enhanced ion removal. Moderate porosity in M3 appears to support efficient water flux and ion transport, whereas higher nanoparticle loadings may cause localized agglomeration, reducing the effective surface area and slightly decreasing heavy metal rejection. Interestingly, Cu^{2+} ions exhibited slightly higher rejection than Cr^{2+} ions, possibly due to stronger coordination interactions between Cu^{2+} and the hydroxyl or oxygen-containing functional groups on the membrane surface [42]. These results are consistent with previous reports highlighting the favorable interaction of copper ferrite-based nanoparticles with divalent cations [43, 44]. Overall, the M3 membrane provides an effective balance of porosity, surface hydrophilicity, and nanoparticle distribution, leading to enhanced heavy metal removal under the studied conditions [45, 46].

3.3.5. Fouling Resistance and Cleaning Efficiency

The antifouling performance of the membranes was evaluated using the optimized $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanocomposite membrane (M3) and the pristine PES membrane (M0) with a protein solution (milk powder) as the fouling agent. The pure water flux (J_{w1}) was measured initially, followed by the flux during protein filtration (J_p), and finally the water flux after cleaning (J_{w2}). The recorded values for both membranes are presented in Figure 8.

A notable decrease in flux was observed during

protein filtration compared to the initial water flux, indicating partial pore blockage and surface deposition of protein molecules. After hydraulic cleaning, the pure water flux partially recovered, suggesting a combination of reversible and irreversible fouling. The flux recovery ratio (FRR), calculated as $J_{w2}/J_{w1} \times 100\%$, is shown in Figure 9. The M3 membrane exhibited a higher FRR than the unmodified PES membrane, indicating improved resistance to fouling under the tested conditions [47]. This enhanced antifouling performance may be associated with changes in surface morphology and hydrophilicity induced by the incorporation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles. Compared to M0, the modified membrane displayed a smoother surface and lower water contact angle, which likely facilitates the formation of a hydration layer on the membrane surface. Such a layer may act as a physical barrier, reducing protein adhesion and mitigating fouling. Additionally, the improved water mobility across the membrane surface may assist in detachment of loosely bound foulants, delaying fouling progression. The overall fouling resistance ($R_t = R_r + R_{ir}$) was further analyzed by differentiating reversible (R_r) and irreversible (R_{ir}) fouling components (Figure 10). Reversible fouling corresponds to loosely bound solutes removable by hydraulic cleaning, whereas irreversible fouling involves more persistent deposits that may require chemical treatment. The M3 membrane exhibited a lower total fouling resistance than M0, with the majority of fouling being reversible. These observations suggest that the incorporation of $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles may contribute to improved fouling mitigation, while preserving membrane functionality under the experimental conditions.

4. Comparison with other literature

A summary of different research studies investigating the removal of contaminants such as dye, heavy metals, and salt is presented in Table 6. These studies, including the current research, indicate that incorporating hydrophilic nanoparticles into the PES membrane matrix is a highly effective approach for reducing these pollutants. Moreover, the results of this study provide evidence that enhancing the PES membrane through the utilization of MOF and nanostructure methods can significantly improve its performance in pollutant removal. The modified PES membrane exhibited a removal efficiency exceeding 80% for salts and over 90% for heavy metals and reactive dyes. Table 6 compares the separation efficiency of the ZIF-8@ (AC-co-CS)/PES membrane with those reported in some recently published articles. The data show that the membrane synthesized in this study achieved the highest rejection rates for various contaminants, including MB, RhB, RB50, RB21, RY145, RY39, Na_2SO_4 , MgSO_4 , CrSO_4 , and CuSO_4 , among different MMMs. The specific solute rejection rates were 96.85% for Na_2SO_4 , 86.05% for MgSO_4 , 97.50% for CrSO_4 , and

96.30% for CuSO_4 . This performance improvement is attributed to incorporating the ZIF-8@ (AC-co-CS) nanocomposite. The exceptionally high separation efficiency of the ZIF-8@ (AC-co-CS)/PES membrane, compared to similar membranes, underscores its cost-effectiveness in filtration processes.

4. CONCLUSION

$\text{CuFe}_2\text{O}_4/\text{Ag}$ hybrid nanoparticles were incorporated as functional modifiers to improve the efficiency of polyethersulfone (PES) nanofiltration membranes. Membranes containing different nanoparticle concentrations were fabricated using the phase inversion method. The synthesized nanocomposite membranes and composite nanoparticle were systematically characterized using Fourier-transform infrared spectroscopy (FTIR), field emission scanning electron microscopy (FESEM), and three-dimensional surface profiling to assess their structural and morphological features. Sodium salt separation and heavy metal ion removal experiments were conducted to evaluate the filtration performance of the modified membranes. Although $\text{CuFe}_2\text{O}_4/\text{Ag}$ nanoparticles inherently

Table 3-Performance Comparison: $\text{CuFe}_2\text{O}_4/\text{Ag}$ /PES membrane vs. reported results.

Polymer and Concentration (wt %)	Membrane type	Additive	Solute rejected (%)	Ref
PES20	NF	$\text{Fe}_3\text{O}_4/\text{SiO}_2\text{-CS}$	Na_2SO_4 :97.75 Methylene Blue:38.25	[48]
PES 18	NF	PES/ NiFe_2O_4	Na_2SO_4 Rejection (%) : 65 Cr(II) Rejection (%) : 65 Cu(II) Rejection (%) : 70	[22]
PES 18	NF	PES/ ZnFe_2O_4	Na_2SO_4 Rejection (%) : 61 Cr(II) Rejection (%) : 63 Cu(II) Rejection (%) : 63	[22]
PES 18	NF	PES/ CoFe_2O_4	Na_2SO_4 Rejection (%) : 78 Cr(II) Rejection (%) : 72 Cu(II) Rejection (%) : 75	[22]
PES 18	NF	Cu_2O	Na_2SO_4 :66.94 $\text{Pb}(\text{NO}_3)_2$:85.08 CrSO_4 :79.38 $\text{Cu}(\text{NO}_3)_2$:81	[49]
PES 18	NF	Ag/Cu	Pb(II):92.6 reactive black 5:96.4 reactive red:98.4	[50]
PES 18	NF	$\text{CuFe}_2\text{O}_4/\text{Ag}$	Na_2SO_4 Rejection (%) : 94 Cr(II) Rejection (%) : 81 Cu(II) Rejection (%) : 93	This work

exhibit hydrophobic characteristics, their integration into the PES matrix resulted in a remarkable enhancement of hydrophilicity, as confirmed by experimental observations. The incorporation of a small amount of hybrid nanoparticles was found to significantly reduce surface roughness and contact angle, thereby enhancing the overall wettability of the membrane surface. Consequently, the pure water flux increased approximately 2.5 times compared with the unmodified PES membrane. In addition, the modified membranes exhibited substantial improvements in separation capability, with rejection efficiencies for Na_2SO_4 , Cr(II) , and Cu(II) increasing by 66%, 25%, and 41%, respectively, compared to the pristine PES membrane. A pronounced enhancement in antifouling behavior was also observed, as the flux recovery ratio (FRR) rose from 61% for the neat membrane to 88% for the optimized nanocomposite membrane (M3), corresponding to nearly a fourfold improvement in fouling resistance and operational durability.

Conflict of Interest

The authors declare that they have no known conflicts of interest.

5. Reference:

1. R. Ben Dassi, B. Chamam, Nanomaterial-enhanced membranes for advanced water and wastewater treatment: a comprehensive review, *Rev. Environ. Sci. Biotechnol.* 24 (2025) 477–511. <https://doi.org/10.1007/s11157-025-09723-9>
2. E. Valamohammadi, F. Behdarvand, T. Mohammadi, M.A. Tofighy, Z. Moghiseh, Effects of carbon nanotubes on structure, performance and properties of polymer nanocomposite membranes for water/wastewater treatment applications: a comprehensive review, *Polym. Bull.* 80 (2023) 11589–11632. <https://doi.org/10.1007/s00289-022-04635-y>
3. B. Arundhati, M. Pabba, S.S. Raj, N. Sahu, S. Sridhar, Advancements in mixed-matrix membranes for various separation applications: state of the art and future prospects, *Membranes* 14 (2024) 224. <https://doi.org/10.3390/membranes14110224>
4. T. Luo, X. Xiao, J. Du, K. Sheng, R. Liu, S. Yuan, P. Jin, J. Zheng, L. Jiang, B. Van der Bruggen, Recent Advances in Polymeric, Inorganic, and Mixed Matrix Membranes for Pervaporation Desalination, *Environ. Chem. Saf.* 1 (2025) 9600006. <https://doi.org/10.26599/ECS.2025.9600006>
5. H.E. Almansouri, M. Edokali, M.N. Abu Seman, E.P. Ndia Ntone, C.K.M.F. Che Ku Yahya, A.W. Mohammad, Antifouling and Desalination Enhancement of Forward Osmosis-Based Thin Film Composite Membranes via Functionalized Multiwalled Carbon Nanotubes Mixed Matrix Polyethersulfone Substrate, *Membranes* 15 (2025) 240. <https://doi.org/10.3390/membranes15080240>
6. A. Sałacińska, P. Sienkiewicz, K. Szymański, S. Mozia, Polyethersulfone mixed matrix membranes modified with pore formers and Ag-titanate nanotubes: physicochemical characteristics and (bio)fouling study, *Environ. Sci. Pollut. Res.* 31 (2024) 63876–63894. <https://doi.org/10.1007/s11356-024-35461-6>
7. F. Zareei, S.M. Hosseini, A new type of polyethersulfone based composite nanofiltration membrane decorated by cobalt ferrite-copper oxide nanoparticles with enhanced performance and antifouling property, *Sep. Purif. Technol.* 226 (2019) 48–58. <https://doi.org/10.1016/j.seppur.2019.05.077>
8. S. Ayazi, M. Ghorbani, R. Abedini, Multifunctional composite membranes incorporated by $\text{SiO}_2/\text{CuFe}_2\text{O}_4$ nanocomposite for high dye removal, antibacterial and antifouling properties, *Chem. Eng. Res. Des.* 169 (2021) 214–228. <https://doi.org/10.1016/j.cherd.2021.03.025>
9. A. Fahrina, N. Arahman, M.R. Bilad, S. Aprilia, S. Mulyati, B.Y. Gül, A. Yuksekdog, S. Korkut, I. Koyuncu, M. Aziz, M. Ulbricht, High-performance of anti-bacterial composite membrane prepared from polyethersulfone-polyethylene glycol-silver nanoparticles, *S. Afr. J. Chem. Eng.* 50 (2024) 404–414. <https://doi.org/10.1016/j.sajce.2024.09.009>
10. R. Patel, M. Patel, R.D. Mohili, K. Mahabari, A.H. Jadhav, S. Dharaskar, M.A. Shabimam, N. Chaudhari, Iron oxide-MXene-based composite for the removal of copper ions from wastewater, *Environ. Sci. Pollut. Res.* 32 (2025) 12108–12120. <https://doi.org/10.1007/s11356-025-36413-4>
11. M.M. Ngoma, M. Mathaba, K. Moothi, Removal of Cu^{2+} , Fe^{2+} , Ni^{2+} , Zn^{2+} and Cl^- from Industrial Wastewater Using a Polyethersulfone/Carbon Nanotube/Polyvinyl Alcohol Composite Membrane, *Environ. Challenges* 4 (2021) 100116. <https://doi.org/10.1016/j.envc.2021.100116>
12. A. Manohar, K.H. Kim, Effect of calcination temperature on the structural, magnetic, and surface characteristics of quaternary $\text{CaFe}_2\text{O}_4/\text{CuFe}_2\text{O}_4/\text{ZnFe}_2\text{O}_4/\text{NiFe}_2\text{O}_4$ ferrite nanocomposites, *Appl. Phys. A* 131 (2025) 730. <https://doi.org/10.1007/s00339-025-08815-1>
13. K.M.M. Abou El-Nour, A. Eftaiha, A. Al-Warthan, R.A.A. Ammar, Synthesis and applications of silver nanoparticles, *Arab. J. Chem.* 3 (2010) 135–140. <https://doi.org/10.1016/j.arabjc.2010.04.008>
14. A. Subha, M.G. Shalini, B.N. Sahu, S. Rout, S.C. Sahoo, Role of surface defects and anisotropy variation on magnetic properties of copper ferrite nanoparticles prepared by co-precipitation method, *Mater. Chem. Phys.* 286 (2022) 126212. <https://doi.org/10.1016/j.matchemphys.2022.126212>
15. J.-R. Chiou, B.-H. Lai, K.-C. Hsu, D.-H. Chen, One-pot green synthesis of silver/iron oxide composite nanoparticles for 4-nitrophenol reduction, *J. Hazard. Mater.* 248–249 (2013) 394–400. <https://doi.org/10.1016/j.jhazmat.2013.01.030>
16. M. Afshari, A. Moghadassi, S.M. Hosseini, Nanocomposite ZIF-8@Active Carbon-co-Chitosan incorporated nanofiltration membrane with enhanced antifouling property and high separation efficiency to salt, heavy metals, and dye solutions, *Arab. J. Chem.* 17 (2024) 105951. <https://doi.org/10.1016/j.arabjc.2024.105951>
17. M.A. Noriega, P.C. Narváez-Rincón, A.C. Habert, Biodiesel separation using ultrafiltration poly(ether sulfone) hollow fiber membranes: Improving biodiesel and glycerol rich phases settling, *Chem. Eng. Res. Des.* 138 (2018) 32–42. <https://doi.org/10.1016/j.cherd.2018.08.013>
18. S.K. Farahani, S.M. Hosseini, A highly promoted nanofiltration membrane by incorporating of aminated Zr-based MOF for efficient salts and dyes removal with excellent antifouling properties, *Chem. Eng. Res. Des.* 188 (2022) 764–778. <https://doi.org/10.1016/j.cherd.2022.10.027>
19. S. Amiri, A. Asghari, V. Vatanpour, M. Rajabi, Fabrication and characterization of a novel polyvinyl alcohol-graphene oxide-sodium alginate nanocomposite hydrogel blended PES nanofiltration membrane for improved water purification, *Sep. Purif. Technol.* 250 (2020) 117216. <https://doi.org/10.1016/j.seppur.2020.117216>
20. S.M. Hosseini, F. Moradi, S.K. Farahani, S. Bandehali, F. Parviziyan, M. Ebrahimi, J. Shen, Carbon nanofibers/chi-

- tosan nanocomposite thin film for surface modification of poly(ether sulphone) nanofiltration membrane, *Mater. Chem. Phys.* 269 (2021) 124720. <https://doi.org/10.1016/j.matchemphys.2021.124720>
21. V. Vatanpour, H. Karimi, S.I. Ghazanlou, Y. Mansourpanah, M.R. Ganjali, A. Badii, E. Pourbashir, M.R. Saeb, Anti-fouling polyethersulfone nanofiltration membranes aided by amine-functionalized boron nitride nanosheets with improved separation performance, *J. Environ. Chem. Eng.* 8 (2020) 104454. <https://doi.org/10.1016/j.jece.2020.104454>
 22. D. Ghanbari, S. BandehAli, A. Moghadassi, Embedded three spinel ferrite nanoparticles in PES-based nano filtration membranes with enhanced separation properties, *Main Group Met. Chem.* 45 (2022) 1–10. <https://doi.org/10.1515/mgmc-2022-0001>
 23. D. Ghanbari, M. Salavati-Niasari, F. Beshkar, O. Amiri, Electro-spinning of cellulose acetate nanofibers: microwave synthesis of calcium ferrite nanoparticles and CA–Ag–CaFe₂O₄ nanocomposites, *J. Mater. Sci. Mater. Electron.* 26 (2015) 8358–8366. <https://doi.org/10.1007/s10854-015-3502-5>
 24. S.M. Khosravi, S.M. Hosseini, V. Vatanpour, Performance improvement of PES membrane decorated by Mil-125(Ti)/chitosan nanocomposite for removal of organic pollutants and heavy metal, *Chemosphere* 290 (2022) 133335. <https://doi.org/10.1016/j.chemosphere.2021.133335>
 25. Y.-H. Zhao, Y.-L. Qian, B.-K. Zhu, Y.-Y. Xu, Modification of porous poly(vinylidene fluoride) membrane using amphiphilic polymers with different structures in phase inversion process, *J. Membr. Sci.* 310 (2008) 567–576. <https://doi.org/10.1016/j.memsci.2007.11.040>
 26. S.T. Nhlengethwa, C.S. Tshangana, B.B. Mamba, A.A. Muleja, The application of TiO₂/ZrO₂-modified nanocomposite PES membrane for improved permeability of textile dye in water, *Membranes* 14 (2024) 222. <https://doi.org/10.3390/membranes14100222>
 27. D. Ashraf, R. Morsi, M. Usman, M.A. Meetani, Recent Advances in the Chromatographic Analysis of Emerging Pollutants in Dairy Milk: A Review (2018–2023), *Molecules* 29 (2024) 1296. <https://doi.org/10.3390/molecules29061296>
 28. P. Daraei, S.S. Madaeni, N. Ghaemi, E. Salehi, M.A. Khadivi, R. Moradian, B. Astinchap, Novel polyethersulfone nanocomposite membrane prepared by PANI/Fe₃O₄ nanoparticles with enhanced performance for Cu(II) removal from water, *J. Membr. Sci.* 415–416 (2012) 250–259. <https://doi.org/10.1016/j.memsci.2012.05.007>
 29. S. Saikova, A. Pavlikov, D. Karpov, A. Samoilov, S. Kirik, M. Volochaev, T. Trofimova, D. Velikanov, A. Kuklin, Copper Ferrite Nanoparticles Synthesized Using Anion-Exchange Resin: Influence of Synthesis Parameters on the Cubic Phase Stability, *Materials* 16 (2023) 2318. <https://doi.org/10.3390/ma16062318>
 30. F. Arabloo, S. Javadpour, Optimization of PES-based Hollow fiber membranes incorporating MgO-modified activated carbon via response surface methodology for enhanced pure water permeability, *Sci. Rep.* 15 (2025) 30044. <https://doi.org/10.1038/s41598-025-15140-3>
 31. J.K. Mann, R. Kurstjens, G. Pourtois, M. Gilbert, F. Dross, J. Poortmans, Opportunities in nanometer sized Si wires for PV applications, *Prog. Mater. Sci.* 58 (2013) 1361–1387. <https://doi.org/10.1016/j.pmatsci.2013.03.001>
 32. S.M. Hosseini, E. Bagheripour, A. Hamidi, A. Moghadassi, S. Madaeni, Fabrication of PES-based nanofiltration membrane modified by composite PAA-co-PMMA-g-ZnA nanoparticles, *J. Iran. Chem. Soc.* 13 (2016) 1749–1758. <https://doi.org/10.1007/s13738-016-0892-0>
 33. Y. Xu, J. Zhang, Y. Liang, J. Zhou, J. Zhao, X. Ruan, Z.P. Xu, G. Qian, Synchronous cyanide purification with metals removal in the co-treatment of Zn–CN and Ni electroplating wastewaters via the Ni²⁺-assisted precipitation of LDH, *Sep. Purif. Technol.* 145 (2015) 92–97. <https://doi.org/10.1016/j.seppur.2015.02.040>
 34. C. De Lannoy, D. Jassby, D. Davis, M. Wiesner, A highly electrically conductive polymer–multiwalled carbon nanotube nanocomposite membrane, *J. Membr. Sci.* 415–416 (2012) 718–724. <https://doi.org/10.1016/j.memsci.2012.05.061>
 35. Y. Li, J. Dai, L. Hong, Y. Guo, D. Zhu, L. Wu, L.-A. Hou, Charge-cascade heterogeneous nanofiltration membrane with enhanced separation and multifunctional anti-fouling for landfill leachate treatment, *Sep. Purif. Technol.* 370 (2025) 133250. <https://doi.org/10.1016/j.seppur.2025.133250>
 36. S.K. Jawad, K.T. Rashid, M.A. Toma, A.A. AbdulRazak, A.D.J. Al-Bayati, Z.M. Shakor, A.S.A. Aljadiri, Q.F. Alsahly, M.A. Shehab, Fabrication, characterization, and modification of a novel polyethersulfone (PES) mix matrix membrane via BiFeO₃ as a hydrophilic additive to improve permeability and antifouling features, *Environ. Sci. Pollut. Res.* 32 (2025) 17563–17584. <https://doi.org/10.1007/s11356-025-36711-x>
 37. S. Chaudhari, S. Chakravarty, Y. Cho, J. Seo, M. Shon, S. Nam, Advancements in Organic Solvent Nanofiltration: The Critical Role of Polyamide Membranes in Sustainable Industrial Applications, *Processes* 13 (2025) 2212. <https://doi.org/10.3390/pr13072212>
 38. N. Bashir, M. Afzaal, A.L. Khan, R. Nawaz, A. Irfan, K.S. Almaary, F. Dabiellil, M. Bourhia, Z. Ahmed, Green-synthesized silver nanoparticle-enhanced nanofiltration mixed matrix membranes for high-performance water purification, *Sci. Rep.* 15 (2025) 1001. <https://doi.org/10.1038/s41598-024-83801-w>
 39. R. Sabouri, B.P. Ladewig, N. Prasetya, Mixed matrix membranes for hydrogen separation: a comprehensive review and performance analysis, *J. Mater. Chem. A* 14 (2026) 681–701. <https://doi.org/10.1039/D5TA00834D>
 40. A. Ghaemi, P. Daraei, A new approach to copper ion removal from water by polymeric nanocomposite membrane embedded with γ -alumina nanoparticles, *Appl. Surf. Sci.* 364 (2016) 221–228. <https://doi.org/10.1016/j.apsusc.2015.12.109>
 41. R. Ramadan, M.M. El-Masry, Effect of (Co and Zn) doping on structural, characterization and the heavy metal removal efficiency of CuFe₂O₄ nanoparticles, *J. Aust. Ceram. Soc.* 60 (2024) 509–524. <https://doi.org/10.1007/s41779-023-00932-5>
 42. A. Pakdel Mojdehi, M. Pourafshari Chenar, M. Namvar-Mahboub, M. Eftekhari, Development of PES/polyaniline-modified TiO₂ adsorptive membrane for copper removal, *Colloids Surf. A Physicochem. Eng. Asp.* 583 (2019) 123931. <https://doi.org/10.1016/j.colsurfa.2019.123931>
 43. Z. Iqbal, M.S. Tanweer, M. Alam, Reduced graphene oxide-modified spinel cobalt ferrite nanocomposite: synthesis, characterization, and its superior adsorption performance for dyes and heavy metals, *ACS Omega* 8 (2023) 6376–6390. <https://doi.org/10.1021/acsomega.2c06636>
 44. K.A. Mohamad Said, A.F. Ismail, Z. Abdul Karim, M.S. Abdullah, J. Usman, M.A. Azali, Magnetic induced asymmetric membrane: Effect of magnetic pattern to phenol removal by adsorption, *Mater. Chem. Phys.* 278 (2022) 125692. <https://doi.org/10.1016/j.matchemphys.2021.125692>
 45. V.V. Vatanpour, A. Shokravi, H. Zarrabi, Z. Nikjavan, A. Javadi, Fabrication and characterization of anti-fouling and anti-bacterial Ag-loaded graphene oxide/polyethersulfone mixed matrix membrane, *J. Ind. Eng. Chem.* 30 (2015) 342–352. <https://doi.org/10.1016/j.jiec.2015.06.004>
 46. S. Mozia, P. Sienkiewicz, K. Szymański, M. Zgrzebnicki, D. Darowna, A. Czyżewski, A.W. Morawski, Influence of Ag/titanate nanotubes on physicochemical, antifouling and antimicrobial properties of mixed-matrix polyethersulfone ultrafiltration membranes, *J. Chem. Technol. Biotechnol.* 94 (2019)

- 2497–2511. <https://doi.org/10.1002/jctb.6039>
47. H. Koulivand, A. Shahbazi, V. Vatanpour, Fabrication and characterization of a high-flux and antifouling polyethersulfone membrane for dye removal by embedding Fe_3O_4 -MDA nanoparticles, *Chem. Eng. Res. Des.* 145 (2019) 64–75. <https://doi.org/10.1016/j.cherd.2019.03.003>
48. S. Kamari, A. Shahbazi, High-performance nanofiltration membrane blended by Fe_3O_4 @ SiO_2 -CS bionanocomposite for efficient simultaneous rejection of salts/heavy metals ions/dyes with high permeability, retention increase and fouling decline, *Chem. Eng. J.* 417 (2021) 127930. <https://doi.org/10.1016/j.cej.2020.127930>
49. A. Moghadassi, S. Ghohyei, S. Bandehali, M. Habibi, M. Eskandari, Cuprous oxide (Cu_2O) nanoparticles in nanofiltration membrane with enhanced separation performance and anti-fouling properties, *Korean J. Chem. Eng.* 40 (2023) 630–641. <https://doi.org/10.1007/s11814-022-1249-2>
50. V. Vatanpour, R. Ardic, B. Esenli, B. Eryildiz-Yesir, P. Yaqubnezhad Pazoki, A. Jarahiyan, F. Matloubi Moghaddam, R. Castro-Muñoz, I. Koyuncu, Defected Ag/Cu-MOF as a modifier of polyethersulfone membranes for enhancing permeability, antifouling properties and heavy metal and dye pollutant removal, *Sep. Purif. Technol.* 345 (2024) 127336. <https://doi.org/10.1016/j.seppur.2024.127336>