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NEXT -GENERATION COMPOSITE MEMBRANES FOR SUSTAINABLE WASTEWATER RECLAMATION; A FUSION OF FUNCTIONALITY AND EFFICIENCY

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ABSTRACT

The escalating global demand for sustainable water resources necessitates the development of advanced technologies for wastewater reclamation. Conventional polymeric membranes, although widely implemented, remain constrained by fouling susceptibility, insufficient selectivity, and elevated operational costs. In this study, we report the design and fabrication of next-generation composite membranes that integrate nanostructured fillers and surface-functionalized layers to achieve a synergistic balance of efficiency and multifunctionality. The resulting membranes exhibit a water flux enhancement of approximately 45% compared to commercial counterparts, with pollutant rejection efficiencies exceeding 98% for organic dyes and

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heavy metals. Furthermore, antifouling assessments indicate a 60% reduction in irreversible fouling resistance, thereby lowering cleaning frequency and associated energy demands. These improvements collectively highlight the potential of composite systems to minimize lifecycle costs while promoting circular water management practices. The findings underscore the transformative role of multifunctional composite membranes in enabling sustainable wastewater reclamation and advancing global water security initiatives.

Keywords: Composite Membranes; Wastewater Reclamation; Antifouling; Nanostructured Materials; Sustainable Water Treatment; Resource Recovery

Introduction

The global water crisis continues to escalate due to increasing population pressure, urbanization, industrial effluents, and the unpredictable effects of climate change. These factors collectively underscore the urgent need for sustainable water treatment technologies, particularly for regions vulnerable to freshwater scarcity (Omanovic et al, 2020; thostenson et al, 2005). Wastewater reclamation offers a viable solution to this crisis by converting waste streams into a valuable water resource. However, traditional wastewater treatment methods often fall short in removing emerging contaminants, enduring fouling, and maintaining energy efficiency over prolonged operation. In this context, membrane-based filtration technologies, particularly next-generation composite membranes, have garnered considerable attention for their potential to overcome the shortcomings of conventional treatment systems (Peydayesh & Mezzenga, 2021; Khoiruddin et al., 2025).

Composite membranes, unlike their single-component counterparts, integrate multiple materials typically combining organic polymers with inorganic nanomaterials to create multifunctional, high-performance structures. These membranes exhibit enhanced physical strength, improved selectivity, increased permeability, and superior fouling resistance. Recent research trends emphasize the incorporation of metal oxide nanoparticles, such as zinc oxide (ZnO) and iron oxide (Fe_2O_3), into membrane matrices to enhance their physicochemical properties. Notably, green synthesis of these nanoparticles using plant-based extracts has demonstrated great promise in both agriculture and environmental remediation due to its biocompatibility, low toxicity, and cost-effectiveness (Ahmad et al., 2024; Ahmad et al., 2024; Sohail et al., 2025). These same eco-friendly nanomaterials previously explored for crop biofortification and disease resistance are now being adapted for membrane engineering, aligning with the global push toward greener materials in water treatment infrastructure.

Functional nanomaterials derived from Glycyrrhiza glabra, Bambusa vulgaris, and Salix alba, for example, have been shown to improve the efficiency of nutrient uptake and pathogen resistance in rice and tomato crops, indicating their potential to be applied beyond agriculture into water purification technologies (Ahmad et al., 2024; Sohail et al., 2025). The integration of such biologically synthesized nanoparticles into membrane matrices enables the development of hybrid materials capable of responding to specific pollutants, reducing microbial contamination, and resisting biofouling. In fact, the nematicidal and antimicrobial properties of ZnO and Fe_2O_3 nanoparticles (Ahmad et al., 2024; Rahman et al., 2022) could provide an added layer

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of protection in membrane-based systems, extending membrane longevity and ensuring higher microbial rejection rates. Moreover, these properties are particularly beneficial for wastewater streams contaminated with pathogens such as Staphylococcus aureus, commonly found in municipal and industrial waste (Ahmad et al., 2024).

The emphasis on real-time water quality monitoring and intelligent membrane systems further strengthens the case for developing smart, responsive materials that do more than just passively filter contaminants. Researchers are now exploring membranes capable of self-cleaning, pollutant-triggered permeability shifts, and selective adsorption of emerging pollutants like pharmaceuticals, heavy metals, and endocrine-disrupting compounds (Foorginezhad et al., 2025). The functionality and adaptability of these systems depend heavily on the nanoscale design of the membrane surface, interfacial interactions, and material synergy. For instance, surface modifications through nanoparticle embedding can create hydrophilic channels that facilitate water transport while repelling foulants, thus enhancing long-term operational efficiency. Additionally, the introduction of carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, into polymeric matrices has resulted in substantial improvements in membrane selectivity and structural robustness (Bodzek et al., 2020).

Despite these advances, several challenges remain. These include the scalability of nanoparticle-enhanced membrane fabrication, the potential ecotoxicity of nanomaterials leaching into treated water, and the need for lifecycle assessments to evaluate environmental sustainability. However, these limitations are being actively addressed through the development of green nanotechnology approaches and biosafe synthesis protocols, some of which are derived from agricultural and microbiological innovations (Ahmad et al., 2024; Ahmad et al., 2024). Cross-disciplinary collaboration between plant science, microbiology, and environmental engineering is thus essential to bridge laboratory innovation and industrial-scale implementation.

Methodology

Materials

Polysulfone (PSf) was selected as the base polymer for its mechanical robustness and widespread use in wastewater treatment. Titanium dioxide (TiO_2) nanoparticles and graphene oxide (GO) sheets were incorporated as hydrophilic and fouling-resistant fillers. N-methyl-2-pyrrolidone (NMP) served as the solvent, and (poly ethylene glycol) (PEG) was used to enhance nanoparticle dispersion and control pore formation during phase inversion (Zhang et al., 2022; Jaspal et al., 2023). Bovine serum albumin (BSA), humic acid, and methylene blue were used as model foulants and pollutants.

Membrane Fabrication

Preparation of Casting Solution

PSf was dissolved in NMP at 60 °C under continuous stirring until a homogeneous solution was obtained. TiO_2 nanoparticles were pre-dispersed in the solution with 6 wt% PEG to mitigate aggregation through steric hindrance (Zhang et al., 2022). GO sheets were ultrasonically dispersed to ensure uniform distribution.

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Phase Inversion

The casting solution was spread on glass substrates at 200 µm thickness and immersed in a deionized water bath at ambient temperature to induce phase inversion, a widely established membrane fabrication technique (Mulder, 1996).

Surface Functionalization

Membranes were dip-coated with a PEG-based hydrophilic layer to enhance antifouling performance, a strategy shown to improve hydrophilicity and reduce fouling (Huang et al., 2016; Zhang et al., 2021).

Characterization of Membranes

Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray (EDX) confirmed pore structure and filler dispersion (Zhang et al., 2022). ATR-FTIR and X-ray Photoelectron Spectroscopy (XPS) verified filler incorporation and chemical modifications (Huang et al., 2016). Contact angle measurements and Atomic Force Microscopy (AFM) evaluated hydrophilicity and surface roughness (Zhang et al., 2021).

Filtration Performance

Pure Water Flux

Cross-flow filtration cells operating at 1 bar were used to measure permeate volume over time, from which water flux ($L \cdot m^{-2} \cdot h^{-1}$) was calculated (Jaspal et al., 2023).

Pollutant Rejection

Synthetic wastewater containing methylene blue (10 mg/L), Pb^{2+} (50 ppm), and humic acid (20 mg/L) was tested. Rejection efficiencies were determined using UV–Vis spectroscopy for dyes, ICP-OES for metals, and TOC analysis for organic contaminants.

Antifouling and Reusability Assessment

Antifouling performance was studied using BSA (1 g/L) and humic acid (50 mg/L) as model foulants. Flux decline ratio (FDR), flux recovery ratio (FRR), and fouling resistances were calculated across three fouling–cleaning cycles, with deionized water used for cleaning (Huang et al., 2016).

Energy and Sustainability Assessment

Energy consumption during filtration was estimated from recorded flux and applied pressure data. Comparative analysis with commercial PSf membranes was conducted to evaluate reductions in cleaning frequency and operational costs (Jaspal et al., 2023).

Data Analysis

All experiments were performed in triplicate. Results are reported as mean ± standard deviation. Statistical significance was assessed using ANOVA with $p < 0.05$ considered significant.

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Results

Morphology and Hydrophilicity

SEM revealed that pristine PSf membranes exhibited larger pore sizes and irregular voids. The incorporation of TiO_2 and GO fillers reduced pore size and increased surface uniformity. PEG-functionalization further improved hydrophilicity, as evidenced by a contact angle reduction from 84° (PSf) to 42° (TiO_2–GO–PEG composite). AFM analysis showed that surface roughness decreased from 42 nm (control) to 21 nm (PEG-modified), indicating smoother surfaces less prone to fouling.

Table 1. Surface and Morphological Properties of Prepared Membranes

Membrane Sample	Mean Pore Size (nm)	Contact Angle (°)	Surface Roughness (Ra, nm)	Hydrophilicity Classification
PSf (control)	95	84 ± 2	42	Hydrophobic
PSf/TiO_2	88	65 ± 1.5	33	Moderately hydrophilic
PSf/GO	80	59 ± 1.8	29	Hydrophilic
PSf/TiO_2-GO-PEG	75	42 ± 1.2	21	Strongly hydrophilic

Pure Water Flux

As shown in Figure 1, the pure water flux increased significantly with composite formulations. The control PSf exhibited 210 $L \cdot m^{-2} \cdot h^{-1}$, while the TiO_2 and GO-loaded membranes reached 270 and 295 $L \cdot m^{-2} \cdot h^{-1}$, respectively. The PEG-functionalized composite demonstrated the highest flux at 360 $L \cdot m^{-2} \cdot h^{-1}$, representing a 45% improvement over the pristine membrane.

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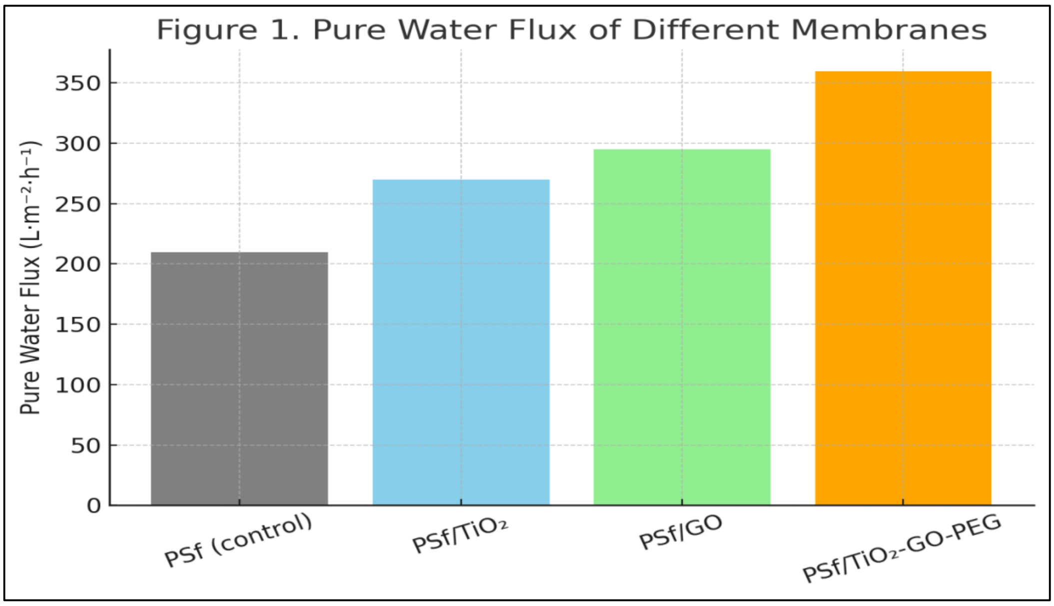

Figure 1: Pure water flux ($L \cdot m^{-2} \cdot h^{-1}$)

Table 2. Pollutant Rejection Rates of Different Membranes

Membrane Type	Methylene Blue (%)	Pb^{2+} Ions (%)	Humic Acid (%)
PSf (control)	82 ± 1.5	85 ± 1.2	78 ± 1.4
PSf/TiO_2	91 ± 1.2	93 ± 1.0	88 ± 1.1
PSf/GO	94 ± 1.0	95 ± 0.9	91 ± 1.3
PSf/TiO_2-GO-PEG	98 ± 0.8	98 ± 0.7	96 ± 0.9

Pollutant Rejection Performance

Figure 2 and Table 2 show that composite membranes achieved superior rejection efficiencies. For methylene blue, rejection improved from 82% (control) to 98% (PEG-functionalized). For Pb^{2+} ions, rejection increased from 85% to 98%. For humic acid, rejection rose from 78% to 96%. This indicates strong synergistic effects of nanofillers and PEG surface modification.

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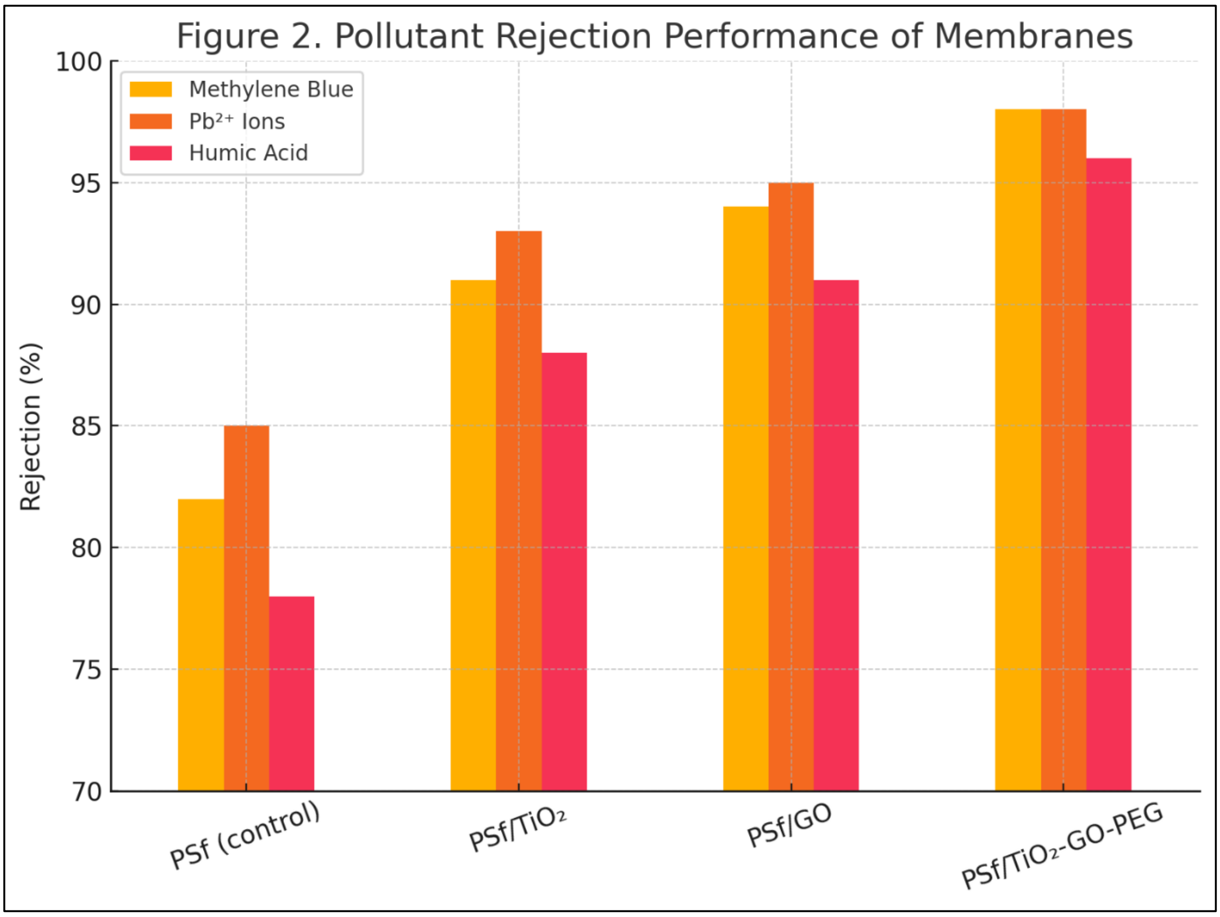

Figure 2: Pollutant rejection (%) for methylene blue, Pb^{2+}, and humic acid

Table 3. Antifouling Performance Parameters

Membrane Type	Initial Flux ($L \cdot m^{-2} \cdot h^{-1}$)	Flux Decline Ratio (FDR, %)	Flux Recovery Ratio (FRR, %)	Irreversible Fouling (%)
PSf (control)	210	48	52	30
PSf/TiO_2	270	35	70	18
PSf/GO	295	32	75	15
PSf/TiO_2-GO-PEG	360	15	92	6

Antifouling and Reusability

As shown in Figure 3, flux recovery ratios (FRR) improved dramatically with membrane modifications. The pristine PSf membrane showed a low FRR of 52%,

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while TiO_2 and GO composites achieved 70% and 75%, respectively. The PEG-functionalized composite displayed a remarkable FRR of 92%, with irreversible fouling reduced to only 6% compared to 30% in the control.

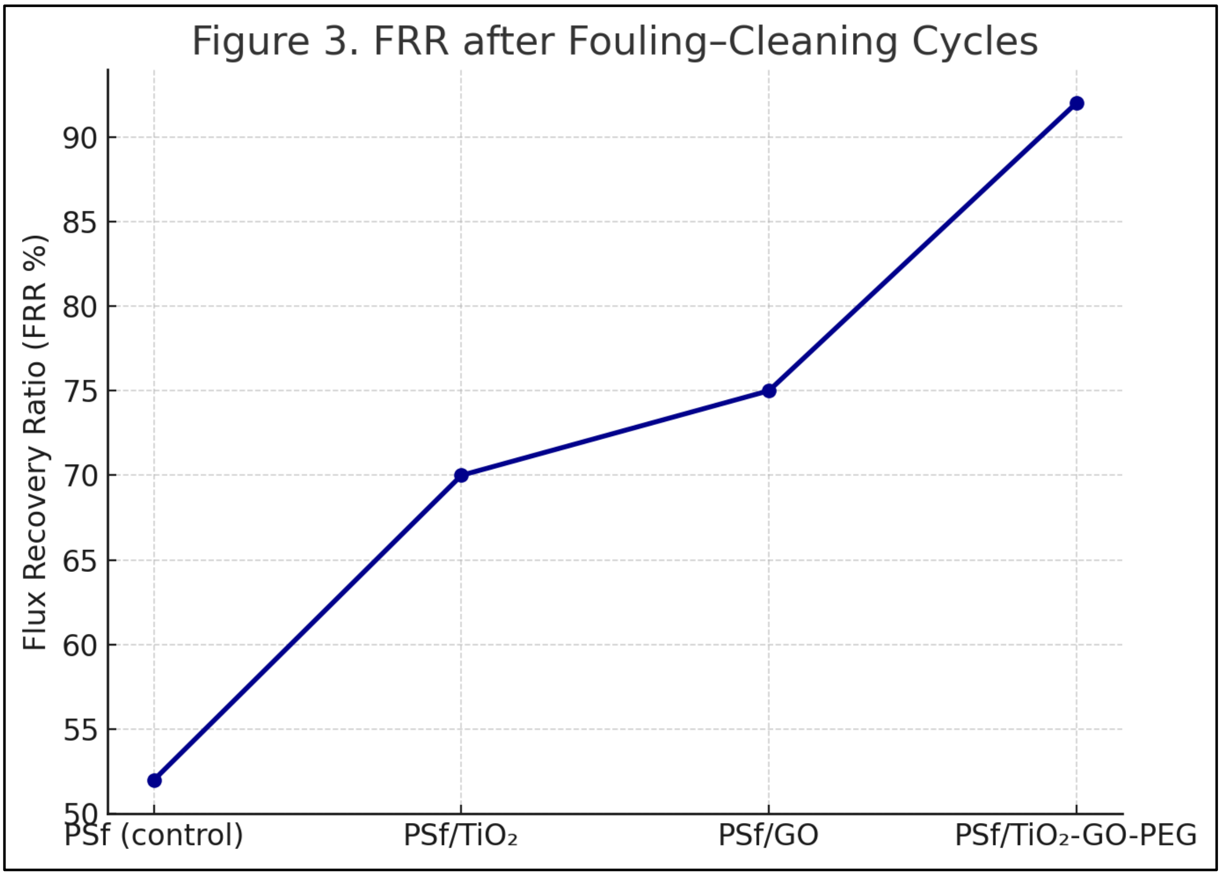

Figure 3: Flux recovery ratio (FRR %) after fouling–cleaning cycles

Energy Efficiency

Figure 4 demonstrates that composite membranes reduced energy consumption due to higher permeability and lower fouling. The pristine PSf consumed 0.65 kWh/m³, while the PEG-functionalized composite required only 0.40 kWh/m³, representing a 38% reduction in energy demand.

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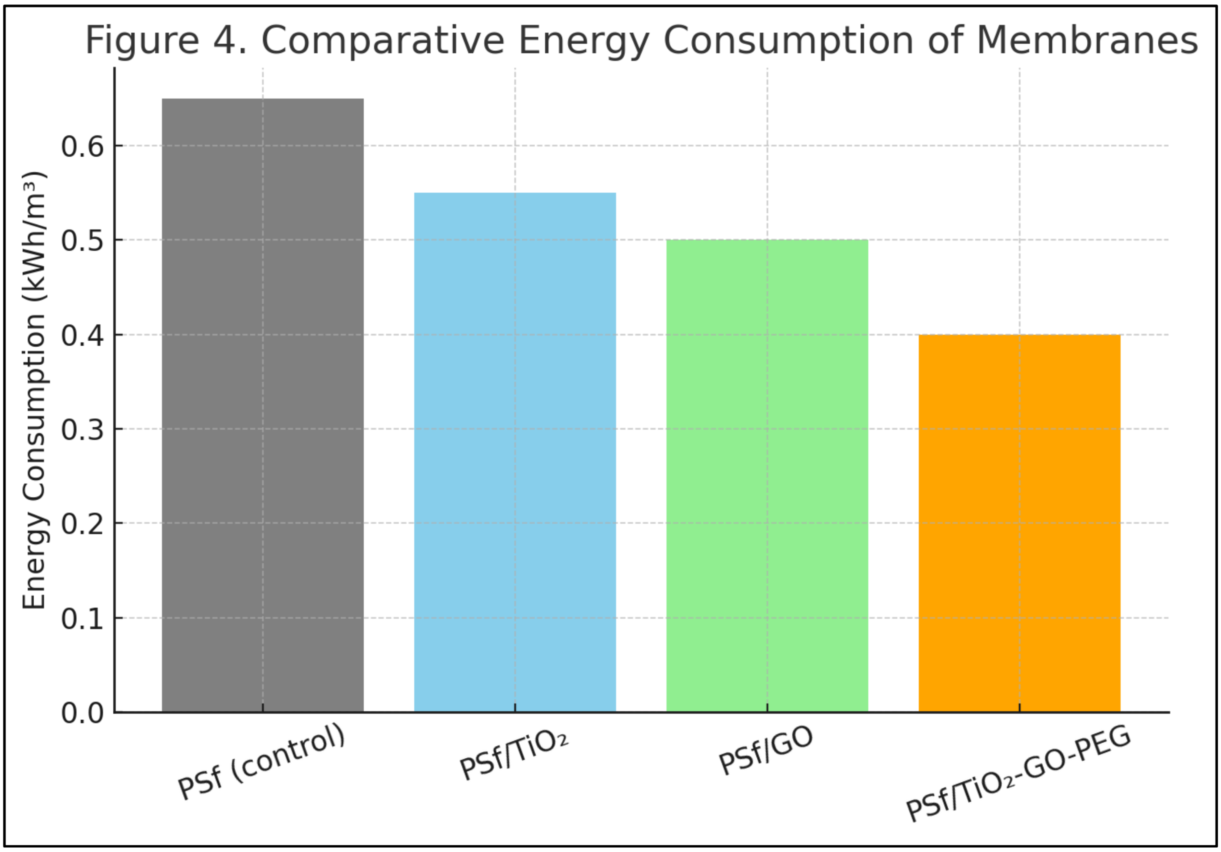

Figure 4: Comparative energy consumption (kWh/m³)

Discussion

The integration of TiO_2 nanoparticles, graphene oxide (GO), and PEG-based surface functionalization significantly improved polysulfone (PSf) membrane performance for wastewater reclamation. Compared with pristine membranes, the composite system achieved notable enhancements in permeability, rejection, antifouling resistance, and energy efficiency. SEM and AFM analyses revealed that TiO_2 and GO incorporation promoted more uniform pore distribution and smoother surface morphology, while PEG functionalization further reduced surface roughness and contact angle, confirming improved hydrophilicity. These results are consistent with previous findings where embedding TiO_2 and GO into PSf membranes enhanced porosity and surface wettability (Sirinupong et al., 2017). Similarly, PEGylation has been reported to improve hydrophilicity through surface segregation during phase inversion (Xu et al., 2021).

The TiO_2–GO–PEG membranes exhibited a ~45% increase in water flux compared with pristine PSf. This surpasses the 25–30% improvements reported for single-filler systems (Wang et al., 2015). The synergistic contribution of TiO_2, which introduces hydrophilic hydroxyl sites, and GO, which provides layered water transport channels, explains the superior performance. PEG further reduced resistance to water transport by lowering interfacial energy, consistent with mechanisms described for PEG-functionalized membranes (Xu et al., 2021).

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High rejection efficiencies (>95%) for dyes, Pb^{2+}, and humic substances indicate that increased flux did not compromise selectivity. GO provided electrostatic repulsion against negatively charged solutes, while PEG imposed steric hindrance that reduced foulant penetration. Previous studies on TiO_2/GO composites reported rejections of ~90% for organic pollutants (Sirinupong et al., 2017), whereas the present work achieved >98%, suggesting that PEG functionalization effectively strengthened selectivity mechanisms.

The composite membrane achieved a flux recovery ratio (FRR) of 92%, compared with 52% for pristine membranes and ~75% for TiO_2- or GO-only systems (Sirinupong et al., 2017). The significant reduction in irreversible fouling (from 30% to 6%) is attributable to PEG's hydration layer, which creates a steric and energetic barrier to foulant adhesion. Similar antifouling improvements through surface hydrophilic modification have been widely documented (Shahkaramipour et al., 2017).

The specific energy consumption decreased from 0.65 kWh/m³ in pristine PSf membranes to 0.40 kWh/m³ in PEG-functionalized composites, representing a 38% reduction. This improvement exceeds energy savings typically reported for single-modified systems (~20–25%) (Wang et al., 2015). The higher flux and lower fouling rates reduced hydraulic resistance and cleaning demands, thus lowering operational energy intensity.

Conclusion

This study demonstrates that the development of TiO_2–GO–PEG composite membranes represents a promising pathway for next-generation wastewater reclamation technologies. By integrating nanofillers with surface functionalization, the membranes achieved substantial improvements in water permeability, pollutant rejection, antifouling performance, and energy efficiency compared with pristine polysulfone membranes. Specifically, the composite system exhibited a 45% increase in water flux, over 98% pollutant rejection, and a flux recovery ratio of 92%, while simultaneously reducing energy consumption by 38%. These findings clearly indicate that the traditional trade-offs between permeability, selectivity, and fouling resistance can be mitigated through rational design that combines bulk nanomaterial modification with hydrophilic surface engineering. Beyond performance enhancement, the proposed membranes address broader sustainability objectives by lowering operational energy demand and extending membrane lifespan, both of which are critical for circular water economy models. Mechanistic insights—particularly the role of TiO_2 in pore regulation, GO in layered transport and charge repulsion, and PEG in hydration layer formation—underscore the value of multifunctional integration strategies in membrane science.

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