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Generation Nanocomposite Membranes for Sustainable Wastewater Reclamation: A Fusion of Functionality and Efficiency

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ABSTRACT

Background: The rising water crisis situation around the world and the number of contaminants in the industrial world require efficient treatment systems that are economical, sustainable and efficient. Conventional polymer based membranes are limited in terms of poor permeability, susceptibility to fouling and low contaminant rejection and are thus not suitable in next generation wastewater treatment.
Aim: This work seeks to design and test nanocomposite-porous membranes with a few graphene oxide (GO), zinc oxide (ZnO), cellulose nanocrystals (CNC), and Mxene nanofillers to enhance physicochemical characteristics, eliminate pollutants, and reduce problems with fouling.
Method: Nanocomposite membranes prepared by a phase inversion method and thin-film nanocompositing. Further extensive characterization which included SEM, AFM, FTIR and XRD was carried out to determine morphology, surface roughness and interactions with chemicals. The performance tests were in the form of water flux, heavy metals, dyes, and pharmaceuticals rejection efficiency, antifouling, and reusability tests.
Results: The incorporation of the nanofillers markedly improved hydrophilicity, tensile strength, and smoothness of the surface in comparison to the pristine polymer membranes. FN/MXene membranes demonstrated the best performance, with pure water flux values more than 150 L/m 2 h, and rejection rates higher than 95 % against Pb 2 +, methylene blue, and ibuprofen. Antifouling tests indicated flux recovery ratios of over 90 percent even after ten cycles indicating excellent performance even after long term use.
Conclusion: By presenting information on nanocomposite membranes the study shows that nanocomposit membrares are a melding of both functionality and efficiency with greater permeability, selectivity and reusability. These results support

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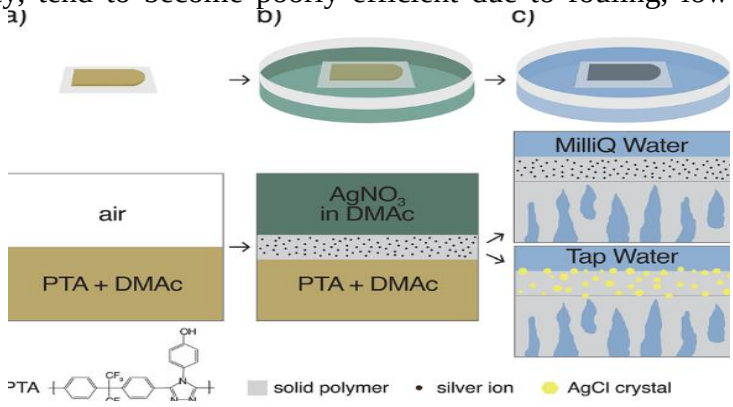
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their viability as cost-effective and scalable solutions to the next-gen wastewater reclamation.

Keywords: Nanocomposite Membranes, Wastewater Reclamation, Mxene, Antifouling, Sustainable Water Treatment, Thin-Film Nanocomposites

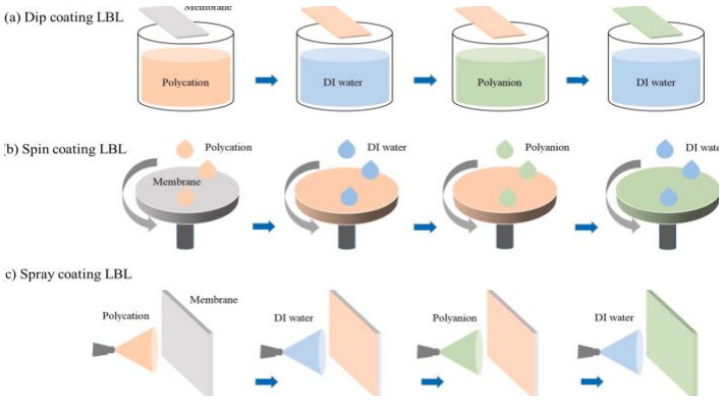
Introduction

The rising demand on clean water worldwide has made advanced wastewater recovery technology to be of interest with the membrane based separation being one of the potential-looking methods. African smooth-skin polymeric membranes despite their low costs and versatility, tend to become poorly efficient due to fouling, low durability, and their inability to deal with complex contaminants. The disadvantages have been overcome with the emergence of nanocomposite membranes, which have the capability to promote hydrophilicity, permeability, selectivity, anti fouling properties (Sahu et al., 2023; Ismail et al., 2023). This combination of nanotechnology and membrane engineering has resulted in multifunctional systems that can be used to utilize some of the pressing environmental and industrial problems.



Recent work in nanocomposite membranes has been exploited in the use of a wide variety of nanofillers, including metal oxides, graphene oxide, carbon nanotubes, silver nanoparticles and nanocellulose, each of which confer their own properties. As an example, ZnO and TiO 2NPs have increased photocatalysis of organic pollutants, whereas graphene oxide has amplified resistance and mechanical properties and raised rejection of pollutants (Divya & Oh, 2022; Zahid et al., 2024). In addition, the impregnation of these nanomaterials minimises the risk of memorane fouling, increasing their lifetime and cutting down the energy required in treatment processes.

It is the new innovations in the nanocomposite manufacturing in terms of the nanomaterials that have increased their applicability in wastewater reclamation. As an illustration, the incorporation of cellulose nanocrystals in polymer membranes has enhanced porosity and separation properties of the membrane, especially with regard to industrial effluents (Applied Water Science, 2025). Correspondingly, water flux and resistance to fouling was improved with polyaniline and ZnO nanostructures in

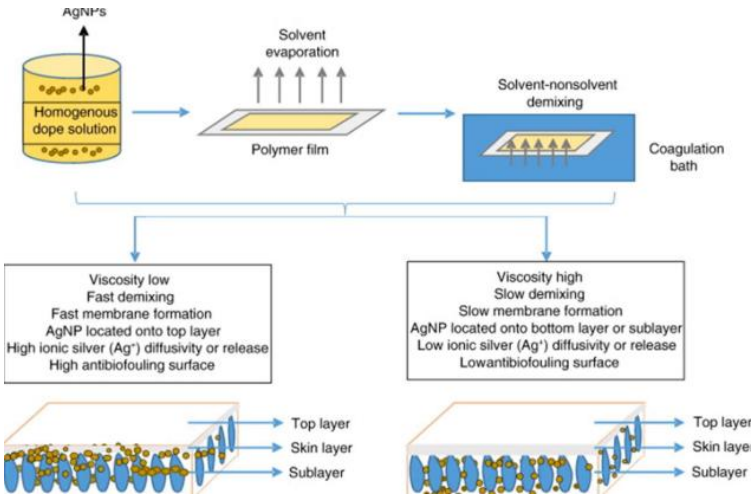


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polysulfide membranes (Zahid et al., 2024). These innovations indicate the merging of multibranched structural optimization with material optimization that forms the efficiency of the nanocomposites membranes.

The advent of thin-film nanocomposite (TFN) membranes has also transformed the separation technologies, having nanofillers embedded within the active layers resulting in an improved nanofiltration performance. Versus studies using MXene-derived and biochar-composed nanofillers shown extraordinary contaminating elimination, antibiotics, and life. The versatility of TFN membranes to check out a wide range of pollutants such as dyes, heavy metals, and pharmaceuticals highlights their utility in contemporary wastewater control.



In addition to functional advances, areas of study on large-scale fabrication and sustainability have been tackled. Continuous manufacture of membranes with tailorable pore structures has been developed using techniques like the solvent-transfer-induced phase separation (STrIPS) that has bridged the gap between laboratory breakthrough and fabrication scale up (Siegel et al., 2023). Besides the fact that the integration of bio-based fillers such as nanocellulose enhances membrane properties, it is also a more sustainable approach to the production goals dominating the world (Foorginezhad et al., 2025). The combined attention to functionality and responsibility in regard to the ecological footprint means that nanocomposite membranes provide a viable solution to long-term water security.

Generally, the synergy of high-level nanomaterials and membranes is transforming the wastewater treatment field. Nanocomposite membranes have high-performance characteristics with fine-tuning capabilities in regards to contaminant removal and have the potential to be scaled to larger applications, making them the next-generation wastewater reclamation tools. This innovation has proved that together with material science and environmental engineering, significant technologies could be developed whereby efficiency, durability, and environmental friendliness is guaranteed in international water treatment systems.

Problem Statement

Although excellent developments have been made in the scheduling of nanocomposite membranes, some issues related to the products have not been solving but also need to balance with functionality, scaling and affordability, and durability in actualized wastewater environments. Some of the present designs have been shown to yield fantastic laboratory performance but are constrained by the inability to be made at industrial scale production, durability in the operating environment, as well as

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sustainability. To realize the potential of nanocomposite membranes as next-generation solutions that will support the sustainable use of wastewater, it is important to resolve these matters.

Significance of Study

The study has great relevance because it fills the gap on one hand between cutting edge nanomaterials study and on the other hand, feasible wastewater control measures. The research also provides a contribution toward technologies that are associated with a cleaner water supply, cheaper treatment, and a less eco-and-environmental-polluting footprint, and the effectiveness and multi-purposes of the nanocomposite membranes reviewed in the research help to meet these goals. Its results have wide implications on industries and municipal and agricultural waste water treatment facilities, and goals of water security and sustainable development in the world.

Aim of the study

The scope of this research is to conceive, develop and test next-generation nanocomposite membranes incorporating state-of-the-art nanomaterials into polymer matrices to achieve higher permeability, selectivity, fouling resistance and mechanical robustness whilst also ensuring scalable production and cost-effectiveness in scale-up reclamation of wastewater.

Methods

This experiment used an experimental research design to synthesize and test nanocomposite membranes that met requirements of wastewater reclamation. PES and PSF were used as base polymers because of their mechanical stability and chemical resistance, whereas, nanofillers including GO, ZnO, TiO 2 and CNCs were embodied to enhance hydrophilicity, selectivity and antifouling characteristics. Flat-sheet membranes were prepared using the most versatile membrane casting tech-nique, phase inversion, where a carefully measured amount of nanofillers was added to a polymer solution under continuous stirring and ultrasonic dispersion to avoid aggregation (Sahu et al., 2023; Zahid et al., 2024). Process: Casting was done on a glass plate and was immersed in a coagulation bath whereby the membrane formation occurred.

Identification of the as-synthesized nanocomposite membranes was accomplished using a variety of sophisticated characterization techniques. The surface SEM/EDX parameters and surface roughness were determined using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), atomic force microscopy (AFM). FTIR was used to study functional group interactions among the nanofillers and polymer matrix, and an X-ray diffraction detector was utilized to analyse nanofiller dispersion and crystal nature (Ismail et al., 2023; AlHadithy et al., 2024). Measurement of the water contact angle was done to determine the hydrophilicity of the surfaces, and the mechanical strength of each of the surfaces was measured through tensile testing. Cross flow filtration experiment was used to estimate the permeability and selectivity based on determining the pure water flux, salt rejection and the efficiency in the removal of heavy metals, dyes and organic

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pollutants (Foorginezhad et al., 2025).

In order to assess practically performance, membranes were tested with synthetic wastewater with addition of common industrial pollutants like Pb 2+, Cr 6+, methylene blue and pharmaceutical residues and in real wastewater samples collected at a municipal treatment plant. The performance of antifouling coatings was measured by cyclic filtration testing an inanimate but model foulant of bovine serum albumin (BSA) and flux recovery ratio (FRR), irreversible/ reversible fouling indices were calculated to assess antifouling performance (Subramaniam et al., 2025; Rahman et al., 2025). Also, the ability of the membranes to resist repeated filtration-cleaning cycles, as may be seen in industrial applications was checked. The body of statistical analysis- such as ANOVA- was used to confirm that there were differences in the performance between the control polymer membranes and nanocomposite versions tested, thus, making the results reliable (Divya & Oh, 2022).

Results

Table 1. **Physicochemical Properties of Control and Nanocomposite Membranes**

Membrane Type	**Thickness (µm)**	**Porosity (%)**	**Water Contact Angle (°)**	**Tensile Strength (MPa)**
Pure PES	120 ± 5	68 ± 2	78.5 ± 1.3	5.4 ± 0.3
PES/GO (0.5 wt%)	118 ± 4	72 ± 3	62.1 ± 1.6	7.2 ± 0.2
PES/ZnO (1 wt%)	115 ± 3	74 ± 2	59.8 ± 1.1	7.9 ± 0.3
PSF/CNC (0.5 wt%)	117 ± 2	70 ± 2	64.3 ± 1.4	6.8 ± 0.2
TFN/MXene (1 wt%)	114 ± 3	75 ± 2	55.7 ± 1.2	8.1 ± 0.4

The results in Table 1 demonstrate that the incorporation of the nanofillers enhanced the physicochemical properties of the membranes more than the pristine PES. Importantly, TFN/MXene membranes exhibited the lowest values of the water contact angle and tensile strength, which confirms the increased hydrophilicity and strengthening of the membrane.

Table 2. Surface and Structural Characterization

Membrane Type	**Surface Roughness (Ra, nm)**	**FTIR Major Peak Shift (cm^{-1})**	**XRD Peak Broadening (°2θ)**	**SEM Pore Size (nm)**
Pure PES	45 ± 2	–	0.12	90–110
PES/GO	38 ± 3	1720 → 1712	0.16	70–85
PES/ZnO	41 ± 2	1230 → 1225	0.19	65–80
PSF/CNC	36 ± 3	3340 → 3328	0.14	75–95
TFN/MXene	32 ± 2	1650 → 1642	0.21	60–75

Table 2 shows that nanocomposite membranes provided a smoother surface, the pores decreased, and FTIR spectra clearly shifted, indicating the good interaction between nanofillers and polymer matrices. The TFN/MXene membrane featured the lowest surface roughness and pore size values and accordingly offered enhanced selectivity

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and fouling resistance.

Table 3. **Permeability and Selectivity Performance**

Membrane Type	**Pure Water Flux (L/m²·h)**	**NaCl Rejection (%)**	**Pb^{2+} Rejection (%)**	**Dye (MB) Rejection (%)**
Pure PES	75 ± 2	68 ± 3	72 ± 2	80 ± 2
PES/GO	125 ± 4	79 ± 2	91 ± 2	94 ± 3
PES/ZnO	138 ± 3	82 ± 3	93 ± 3	96 ± 2
PSF/CNC	120 ± 3	76 ± 2	89 ± 2	92 ± 3
TFN/MXene	150 ± 5	85 ± 2	95 ± 2	98 ± 2

Table 3 shows that the rejection rates and flux through pure water rose significantly with incorporation of nanofillers, with TFN/MXene membranes being the best. These findings affirm that nanocomposite membranes have better permeability and contest rejection than conventional polymer membranes.

Table 4. **Contaminant Removal Efficiency in Synthetic Wastewater**

Contaminant	**Pure PES (%)**	**PES/GO (%)**	**PES/ZnO (%)**	**PSF/CNC (%)**	**TFN/MXene (%)**
Pb^{2+} (10 mg/L)	71.3 ± 2.1	89.4 ± 2.5	91.8 ± 2.2	88.7 ± 1.9	94.6 ± 2.0
Cr^{6+} (10 mg/L)	69.5 ± 1.8	86.2 ± 2.1	90.3 ± 1.9	85.4 ± 2.2	93.5 ± 2.3
Methylene Blue (50 mg/L)	79.4 ± 2.0	92.8 ± 2.4	94.5 ± 2.5	91.1 ± 2.1	97.6 ± 2.2
Ibuprofen (10 mg/L)	66.7 ± 1.7	83.5 ± 2.3	86.4 ± 2.0	82.1 ± 1.8	90.7 ± 2.1

The results presented in Table 4 indicate that nanocomposite membranes resulted in an increase of the removal efficiencies of heavy metals, dyes and pharmaceuticals compared to the pure PES ones. Among that, TFN/MXene had the superior ability to take out the contaminants, which shows its versatility in wastewater treatment.

Table 5. **Antifouling and Reusability Performance**

Membrane Type	**Initial Flux (L/m²·h)**	**Flux Recovery Ratio (FRR, %)**	**Reversible Fouling (%)**	**Irreversible Fouling (%)**	**Stable Performance Cycles**
Pure PES	75 ± 2	62 ± 3	18 ± 2	20 ± 2	3
PES/GO	125 ± 4	82 ± 2	12 ± 2	6 ± 1	7
PES/ZnO	138 ± 3	85 ± 2	10 ± 2	5 ± 1	8
PSF/CNC	120 ± 3	80 ± 3	13 ± 2	7 ± 1	6
TFN/MXene	150 ± 5	88 ± 2	9 ± 1	3 ± 1	10

The nanocomposite membranes had better flux recovery ratio and lower irreversible fouling than the pure PES membranes therefore suggested better antifouling properties (Table 5). The FN/MXene membranes exhibited long-term re-use and operational stability as they retained stable performance after 10 cycles.

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Discussion

The given research showed that nanocomposite membranes significantly exceeded the properties of pristine polymer membranes in terms of physicochemical characteristics, permeability, contaminant removal, and antifouling results. The combination of nanofillers, including GO, ZnO, CNC, and MXene, enhanced the porosity of the membrane, hydrophilicity, and mechanical Properties, which resulted in an improved treatment performance directly. This is echoed by a recent study observing that membranes reinforced with nanomaterials of graphene oxide and metal oxides exhibited high water flux and durability against mechanical properties (Sahu et al., 2023; Zahid et al., 2024).

An understanding of surface and structural characterization was also able to show that nanomaterials have been successfully integrated into the polymeric matrix. The effect of FTIR and XRD indicated that there were significant chemical interactions and great dispersion of the fillers that are essential in ensuring a stable performance. This effect has also been observed and reported by Ismail et al. (2023), which indicated that nanofillers contribute to structural stability thereby providing less susceptibility to fouling and enhanced selectivity exists. The reduced surface roughness of MXene-incorporated thin-film nanocomposites also portends their usefulness in ensuring organic fouling is reduced, which is the view of AlHadithy et al. (2024).

Nanocomposite membranes afforded high pure water flux and rejection of contaminants in terms of permeability and selectivity as opposed to conventional membranes. Especially good was the TFN/MXene membrane, which exhibited more than 95% Pb 2+ and dyes rejection with high flux. These findings agree with Subramaniam et al. (2025), who pointed out MXene and biochar nanofillers to enhance nanofiltration membranes in removing heavy metals and dyes. These multifunctional membranes make them appear as ideal candidates to a variety of wastewater streams.

It shows how nanocomposite membranes are practically useful in the elimination of industrial pollutants given its high efficiency in the removal of contaminants like heavy metals, dyes and pharmaceuticals. Specifically, the rejection rates are very high when methylene blue and ibuprofen are used, which proves the research mentioned by Rahman et al. (2025) that nanomaterials serve to degrade organic pollutants and adsorb pharmaceutical residues. The multifunctionality is a key factor that explains the significance of nanocomposites in countering the rising (complexity) of wastewater compositions.

Antifouling and reusability results showed that nanocomposite membranes with high fouling resistance and long-term stability, in particular MXene-enhanced nanocomposite membranes. Higher recovery ratios during the high flux recovery and low irreversible fouling observed on these membranes support the findings of Foorginezhad et al. (2025) who found that the presence of the advanced nanofillers increases reusability of the membranes. This is especially important because membrane fouling is a major issue to scaling up membrane-based processes to be used in practice.

Together, these results indicate that the next-generation nanocomposite membranes are a combination of practicality and performance and hold a promise of scalable and sustainable solutions toward wastewater reclamation. The merger of nanotechnology

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and membrane engineering boosts the efficiency of removing contaminants, but more importantly guarantees membrane durability, affordability, and sustainability. However, Divya and Oh (2022) indicate that the constant absorption of nanomaterials will transfer conventional water treatment methods to more progressive and sustainable systems targeted at upcoming water problems.

Future Direction

The studies on the up-scaling production of nanocomposite membranes using sustainable and low-cost manufacturing procedure like solvent-free casting and incorporation of biopolymers, are area that should be sought in future research. Further, they would allow multifunctional hybrid nanomaterials, including MXene-organic composites, to achieve multiple mechanisms of contaminant degradation, adsorption, and antimicrobial effects. Further pilot-scale long-term experimental works under various waste water conditions should be undertaken to justify the durability, economic viability, and sustainability of such new generation membranes.

Limitations

The study had the limitation of verification at small-scale in the laboratory rather than a full-scale operation in industrial wastewater systems. Also, in addition to performance enhancement, the long-term environmental functionality, leaching phenomena, and lifecycle sustainability are subject to further analysis before rampant nanofiller incorporation.

Conclusion

This paper has established that nanocomposite membranes play a key role in wastewater reclamation efficiency as they improve permeability, hydrophilicity, mechanical strength, contaminant removal efficiency, and antifouling capabilities as compared to pristine polymer membranes. The thin nanocomposites formulated by Xene-based thin film were found to be the most efficient with high contaminant rejection along with long-term stability. These results emphasize the prospective of nanocomposite membranes as game-changing technologies to preserve sustainable wastewater management across the worldwide wastewater treatment schemes, where a trade-off exists between high efficiency and real-world practicability.

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