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Development and Evaluation of GO/TiO₂-Functionalized Thin-Film Nanocomposite Membranes for Advanced Water Purification

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Abstract

The increasing occurrence of dissolved salts, toxic metals, persistent organic contaminants, pathogenic microorganisms, and membrane-fouling constituents has created a need for water purification systems that combine high selectivity with low energy demand and regenerability. This methodology paper proposes an integrated experimental framework for evaluating functionalized nanomaterials in thin-film nanocomposite (TFN) membranes for advanced water purification. A conventional polyamide thin-film composite (TFC) membrane is used as the control and is compared with graphene oxide (GO), titanium dioxide (TiO₂), and hybrid GO/TiO₂-functionalized membranes. The protocol combines membrane fabrication by phase inversion and interfacial polymerization, physicochemical characterization, cross-flow filtration, contaminant rejection tests, antifouling assessment, antibacterial screening, photocatalytic regeneration, and nanoparticle-leaching analysis. Performance is quantified using water permeance, solute rejection, normalized flux decline, flux recovery ratio, log bacterial reduction, and membrane stability. To demonstrate the planned data-analysis pathway without representing unperformed experiments as real measurements, an explicitly labelled literature-informed illustrative dataset is included. The framework is designed to determine whether nanomaterial functionalization can improve water transport, separation, fouling resistance, and operational durability simultaneously. It also incorporates safety and scalability criteria, which are essential because nanomaterial release and manufacturing complexity can offset treatment benefits. The methodology provides a reproducible basis for laboratory studies of next-generation membrane systems for drinking-water polishing, industrial wastewater reuse, and desalination pretreatment.

Introduction

Access to high-quality water is increasingly constrained by population growth, industrial discharge, salinity intrusion, microbial contamination, and emerging pollutants. Conventional clarification, adsorption, biological treatment, and disinfection remain essential, but

many systems struggle with trace contaminants, high dissolved-solids loads, or the need for compact treatment trains. Shannon et al. [1] identified selective separations, lower energy consumption, advanced materials, and better contaminant destruction as core scientific priorities for future water purification.

Membrane processes directly address several of these priorities because they provide a physical barrier that can be engineered from the microfiltration scale to reverse osmosis. However, practical membrane operation is limited by permeability-selectivity trade-offs, organic and biological fouling, chlorine sensitivity of polyamide layers, concentration polarization, and replacement cost [2].

Nanotechnology offers a route to modify interfacial transport rather than simply increasing membrane pressure. Nanomaterials possess high specific surface area, tunable surface charge, catalytic activity, antimicrobial behavior, and nanoscale dimensions compatible with polymeric separation layers. Qu et al. [3] summarized applications of nanoadsorbents, nanocatalysts, magnetic nanoparticles, and nanostructured membranes for water and wastewater treatment, while later work emphasized that the value of nanotechnology depends on integration with realistic treatment systems rather than material performance alone [9]. The key design challenge is therefore to introduce a nanomaterial into a membrane in a manner that improves hydrophilicity, contaminant affinity, or fouling resistance without generating defects or releasing nanoparticles into treated water.

Graphene oxide is attractive because oxygen-containing functional groups make its surface hydrophilic and chemically modifiable, while two-dimensional nanosheets can create rapid water-transport pathways. GO-enhanced polyamide thin-film nanocomposites have shown improved flux and separation behavior [4], and GO embedded in thin-film composite membranes has also been studied for desalination [5]. Titanium dioxide is complementary: TiO_2 is hydrophilic, chemically stable, and photocatalytically active under suitable irradiation, allowing the membrane surface to participate in organic-foulant degradation. Reviews of antifouling and nanocomposite membranes show that carbon nanomaterials, metal oxides, silver, and related additives can enhance permeability, fouling resistance, mechanical properties, or disinfection when dispersion and loading are carefully controlled [7,8,10].

This paper develops a comparative methodology centered on four membrane configurations: an unmodified polyamide TFC control, a GO-functionalized TFN membrane, a TiO_2 -functionalized TFN membrane, and a hybrid GO/ TiO_2 TFN membrane. The objective is not to claim a specific new material as superior before experimentation; instead, it provides a controlled framework for answering four questions: (i) does

nanomaterial functionalization improve water permeance without sacrificing salt and contaminant rejection, (ii) does surface modification reduce organic and biological fouling, (iii) can TiO_2 -containing membranes recover performance after UV-assisted cleaning, and (iv) is performance improvement achieved without unacceptable nanomaterial leaching? These questions reflect the broader requirement that next-generation membranes combine selectivity, stability, and safe deployment [6,9,16].

Literature Review

Membrane nanotechnology evolved from two parallel directions: improving the polymeric membrane itself and adding nanoscale functions that conventional polymers do not possess. Pendergast and Hoek [2] reviewed early membrane nanotechnologies and distinguished nanostructured materials, nanoparticle-containing mixed matrices, thin-film nanocomposites, and surface-functionalized membranes. The central benefit of these approaches is the possibility of changing water affinity, surface charge, free volume, or biological interactions at the membrane-water interface. Werber et al. [6] later argued that future purification membranes should focus on selectivity and molecular-level transport control rather than permeability alone, because excessive permeability can provide diminishing system-level energy benefits once hydraulic losses elsewhere dominate.

Carbon-based nanomaterials became important because they combine large surface area with tunable chemistry. In polyamide TFN systems, Yin et al. [4] reported that GO incorporation could enhance membrane hydrophilicity and water purification performance, while Ali et al. [5] demonstrated GO-containing thin-film composite membranes for desalination. The effect of GO is not determined only by its concentration. Cheng et al. [11] showed that nanosheet surface exposure strongly influences biofouling resistance: GO-coated and GO-blended membranes can have similar bulk properties but different antibacterial behavior when the active nanosheets are differently exposed. This finding is methodologically important because it supports measuring surface composition and bacterial attachment rather than assuming that adding GO automatically provides antibiofouling performance.

Metal-oxide nanomaterials provide a second functional route. TiO_2 can increase hydrophilicity and provide photocatalytic activity, while ZnO , Fe_3O_4 , CeO_2 , and other oxides can contribute antibacterial, adsorptive, magnetic, or redox

functions. Ursino et al. [8] reviewed major nanocomposite membrane classes and highlighted both improved water treatment performance and persistent concerns about nanoparticle aggregation and stability. Polymeric nanocomposite reviews similarly show that the type, size, surface chemistry, and dispersion of fillers determine whether permeability increases or whether non-selective defects form [10]. Consequently, an optimized nanofiller loading is generally preferable to simply maximizing nanomaterial content.

Functionalization methods have broadened beyond blending. Electrospun nanofiber membranes can be modified before or after electrospinning to provide adsorption, photocatalysis, antimicrobial activity, and size-selective filtration [12]. Nanomaterials have also been incorporated into membrane bioreactors to reduce fouling and extend membrane functionality; Pervez et al. [13] reviewed such nanomaterial-MBR systems and emphasized the need to balance treatment efficiency, membrane fouling control, cost, and environmental release.

These studies support a multi-metric evaluation strategy rather than single-endpoint testing.

More recent reviews up to 2022 reinforce this integrated view. Khraisheh et al. [14] reported that nanomaterial incorporation can improve permeability, mechanical strength, separation, and fouling resistance, but also noted dispersion and compatibility challenges. Lim et al. [15] reviewed biological, biomimetic, and synthetic water channels as emerging routes to highly selective transport, showing how membrane research is shifting toward nanoscale transport architecture. Lazarenko et al. [16] summarized advances in carbon-nanomaterial membranes, while Al Harby et al. [17] placed additional emphasis on scalability, health, and environmental impacts. Together these studies indicate a gap in many laboratory comparisons: excellent short-term flux or rejection is frequently reported, but fewer protocols simultaneously quantify contaminant rejection, fouling, regeneration, and nanomaterial retention under comparable operating conditions. The methodology below is designed to address that gap.

Table 1. Selected literature guiding the methodology

Reference	Material/technology	Main contribution	Methodological implication
[4], [5]	GO-polyamide TFN	GO improves interfacial transport and desalination performance	Compare GO functionalization with a TFC control
[8], [10]	Nanocomposite membranes	Nanofillers can improve flux and fouling resistance but may aggregate	Use multiple loadings and stability checks
[11]	GO surface functionalization	Surface exposure influences antibiofouling behavior	Measure surface properties and bacterial response
[12]	Functionalized nanofibers	Functionalization enables adsorption, photocatalysis and antimicrobial effects	Include multifunctional endpoints
[13], [14]	Nanomaterial membranes/MBR	Benefits must be balanced against fouling, cost and compatibility	Evaluate fouling and regeneration
[16], [17]	Carbon/polymeric nanocomposites	Scalability and environmental safety are critical	Include leaching and scale-up criteria

Methodology

The proposed study uses a controlled laboratory comparison of four thin-film membranes. The membrane chemistry is selected because polyamide TFC membranes are a mature desalination and nanofiltration platform, while GO and TiO₂ represent two widely studied nanomaterial families with complementary hydrophilic, antifouling, and catalytic functions [4,5,8,14]. All experiments should be conducted

in triplicate unless otherwise stated, and the order of membrane testing should be randomized to minimize systematic bias.

Step 1 - Membrane configurations and materials
Four configurations are prepared: M0, a conventional polyamide TFC control; M1, a GO-functionalized TFN membrane; M2, a TiO₂-functionalized TFN membrane; and M3, a hybrid GO/TiO₂-functionalized TFN membrane. A porous polysulfone support is produced by

nonsolvent-induced phase inversion. The selective polyamide layer is then formed by interfacial polymerization between m-phenylenediamine (aqueous phase) and trimesoyl chloride (organic phase). GO nanosheets are introduced at a low loading selected from preliminary dispersion tests, and TiO₂ nanoparticles are incorporated at a concentration that does not visibly agglomerate. The hybrid membrane combines both fillers at the lowest individual loadings that provide stable dispersions. A surface-anchoring step based on a thin polydopamine-like interfacial layer may be used for GO exposure because surface-accessible GO has been associated with stronger antibiofouling behavior [11].

Step 2 - Nanomaterial dispersion and membrane fabrication control

Nanomaterial dispersions are sonicated under identical energy and time conditions. Particle size distribution and zeta potential are recorded before use to confirm dispersion stability. The membrane fabrication variables kept constant are support thickness, polymer concentration, coagulation-bath temperature, monomer concentrations, interfacial polymerization time, curing temperature, and wash procedure. This design isolates the effect of nanomaterial functionalization. Coupons are stored in ultrapure water at 4 °C and tested within a fixed period. At least three independently fabricated membranes per condition are recommended to distinguish true material effects from batch-to-batch variation.

Step 3 - Physicochemical characterization

Surface and cross-sectional morphology are examined by scanning electron microscopy (SEM). Fourier-transform infrared spectroscopy (FTIR) is used to confirm characteristic functional groups, and static water-contact-angle measurements quantify changes in hydrophilicity. Atomic-force microscopy may be used to determine roughness, while streaming-potential or zeta-potential measurements characterize surface charge. Nanomaterial distribution is assessed by elemental mapping where available. These measurements are necessary because the literature shows that nanomaterial location and exposure can be as important as total loading [11,16].

Step 4 - Cross-flow filtration and contaminant challenge

A laboratory cross-flow cell is operated at 25 ± 1 °C. Membranes are first compacted with ultrapure water until flux stabilizes, after which pure-water permeance is calculated from $J/(\Delta P)$, where J is water flux and ΔP is transmembrane pressure. A mixed synthetic feed is then used in separate controlled tests: 2,000 mg L⁻¹ NaCl for

ionic rejection, 10 mg L⁻¹ Pb(II) for toxic-metal retention, and 20 mg L⁻¹ methylene blue as a model organic dye. Separate feeds are preferable to a single complex mixture during primary comparison because they allow unambiguous rejection mechanisms. Solute rejection is calculated as $R = (1 - C_p/C_f) \times 100$, where C_p and C_f are permeate and feed concentrations. Conductivity, ICP-OES/AAS, and UV-visible spectrophotometry are used for NaCl, Pb(II), and dye analysis, respectively.

Step 5 - Fouling, antibacterial activity and regeneration

Organic fouling is evaluated using bovine serum albumin (BSA; 500 mg L⁻¹) or humic acid (20 mg L⁻¹) in a defined ionic background. After a baseline-water flux is recorded, the foulant solution is filtered for a fixed period, followed by standardized hydraulic cleaning. Flux recovery ratio is calculated as $FRR = J_r/J_0 \times 100$, where J_0 is initial pure-water flux and J_r is recovered flux after cleaning. Biofouling resistance is evaluated with *Escherichia coli* using static adhesion or dynamic filtration, reporting viable-cell reduction relative to the control. TiO₂-containing membranes are additionally exposed to a controlled UVA regeneration step, for example 365 nm irradiation for 30 min, and then retested to determine whether photocatalytic cleaning restores flux. Functionalized electrospun and nanocomposite systems in the literature demonstrate the importance of evaluating multiple functions rather than separation alone [12–14].

Step 6 - Nanomaterial leaching, durability and quality assurance

Permeate and cleaning solutions are analyzed for Ti and other relevant elements using ICP-OES/ICP-MS, while carbon-based nanomaterial loss may be assessed indirectly by total organic carbon and membrane mass balance, supported by post-test microscopy. Five filtration-cleaning cycles are recommended. A membrane should not be classified as improved if high initial performance is accompanied by severe loss of nanomaterial or rapid decline over repeated cycles. Blank analytical samples, calibration standards, duplicate samples, and mass-balance checks are included. Nanomaterial safety is treated as a performance criterion because environmental release and scalability are recognized limitations of nano-enabled water treatment [9,17].

Step 7 - Statistical and decision analysis

For each metric, means and standard deviations are calculated from independent replicates. One-way ANOVA followed by Tukey's post-hoc test is proposed for normally distributed data; otherwise, a Kruskal-Wallis's test is used.

Statistical significance is set at $p < 0.05$. In addition to significance testing, a multi-criteria performance index can normalize permeance, rejection, FRR, bacterial reduction, and leaching. The final membrane ranking should therefore reflect balanced performance rather than maximizing a single property, consistent with the broader membrane-design perspective described by Werber et al. [6] and Mauter et al. [9].

Step 8 - Reproducibility, uncertainty and reporting

A reproducible membrane study should distinguish fabrication replication from repeated measurements on the same coupon. At least three independently fabricated membrane batches are recommended for the main comparison; multiple readings from one coupon should be averaged before inferential statistics so that pseudo-replication is avoided. Instrument calibration curves for UV-visible spectrophotometry and metal analysis should meet a predefined

acceptance criterion, and method blanks, spiked samples, and duplicate analyses should be included. Contact-angle data should be collected at several surface positions because nanocomposite membranes can be heterogeneous. Cross-flow experiments should report membrane area, channel geometry, cross-flow velocity, pressure, temperature, feed pH, ionic strength, and sampling times so that hydraulic conditions can be reproduced. Uncertainty should be presented as standard deviation or confidence intervals rather than as single values. Finally, raw flux-time traces, calibration equations, membrane fabrication batches, rejected outliers, and cleaning conditions should be archived with the study. This reporting discipline is especially important for nano-enabled membranes because small changes in nanofiller dispersion, surface exposure, or fabrication conditions can alter both separation and fouling performance [11,14,17].

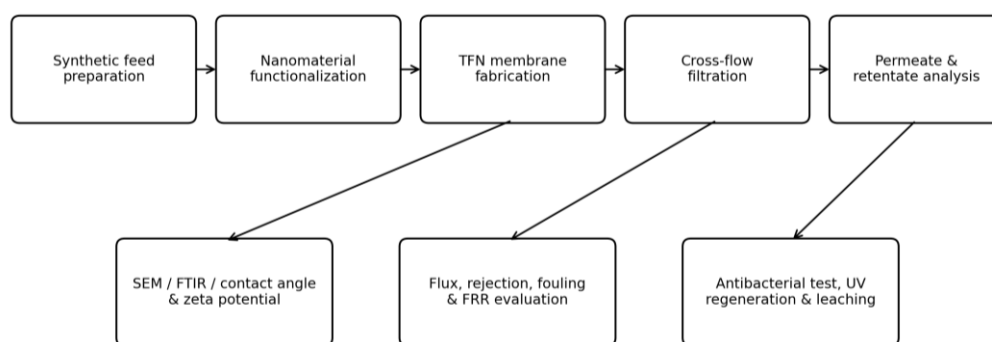


Figure 1. Proposed experimental workflow for evaluating functionalized nanomaterial membranes.

Table 2. Experimental membrane matrix and principal response variables

Code	Membrane	Functional role	Primary measurements	Replicates
M0	Polyamide TFC	Baseline	Permeance; rejection; fouling	≥3
M1	TFN-GO	Hydrophilicity / antibiofouling	Permeance; rejection; FRR; bacteria	≥3
M2	TFN-TiO ₂	Hydrophilicity / photocatalysis	Permeance; FRR; UV recovery; leaching	≥3
M3	TFN-GO/TiO ₂	Combined functionality	All metrics + durability	≥3

Results

Because this is a methodology paper rather than a report of completed laboratory experiments, the numerical values in Table 3 and Figure 2 are an illustrative, literature-informed dataset used only to demonstrate the proposed calculations, comparison logic, and expected reporting format. They must not be interpreted as measured results. A real study should replace every

illustrative value with experimental mean $\pm$ standard deviation and statistical significance. The illustrative comparison shows the expected pattern that motivates the experimental design. Relative to the TFC control, modest GO or TiO₂ functionalization can increase apparent water permeance by increasing membrane hydrophilicity and altering nanoscale transport pathways, while salt rejection is maintained or slightly improved when the nanomaterial is well

dispersed. A hybrid membrane can therefore be hypothesized to provide the largest balanced improvement, but this must be verified because

excessive loading may produce non-selective defects. The same trade-off is emphasized across nanocomposite membrane reviews [8,10,14].

Table 3. Illustrative methodology-validation dataset (not measured experimental data)

Membrane	Permeance ($\text{L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$)	NaCl rejection (%)	Pb(II) rejection (%)	Dye rejection (%)	FRR (%)	Relative bacterial viability (%)
M0 TFC	2.1	96.2	94.0	97.5	72	100
M1 TFN-GO	2.8	97.1	97.0	99.0	88	38
M2 TFN-TiO ₂	2.6	96.8	96.5	98.8	91	44
M3 TFN-GO/TiO ₂	3.0	97.5	98.3	99.4	94	24

In the illustrative dataset, the hybrid membrane has a 42.9% higher water permeance than the TFC control while preserving high NaCl rejection. Its FRR is also higher, suggesting a more reversible fouling layer, and the lower relative bacterial viability is consistent with the hypothesis that accessible GO and a hydrophilic nanocomposite surface can suppress attachment.

This interpretation is compatible with observations that GO surface exposure affects biofouling resistance [11]. For TiO₂-containing membranes, the key additional endpoint is recovery after UV-assisted cleaning; a strong post-irradiation flux recovery would support a photocatalytic self-cleaning contribution rather than hydrophilicity alone.

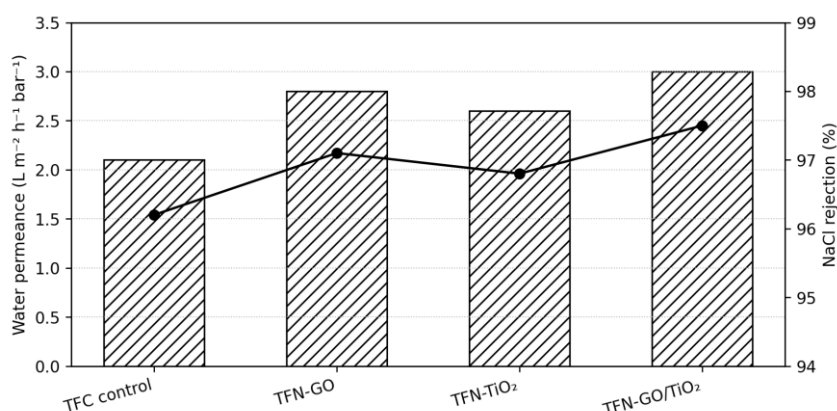


Figure 2. Illustrative relationship between water permeance and NaCl rejection for the four membrane configurations.

A complete results section should also report contact angle, roughness, zeta potential, SEM evidence of defect formation, and nanomaterial leaching. These checks prevent a misleading conclusion based only on flux and rejection. A membrane would be rejected from scale-up consideration if Ti or carbon-based material release increases during repeated cleaning, if salt rejection declines materially over cycles, or if the membrane requires a fabrication route that is difficult to reproduce. Al Harby et al. [17] specifically emphasize scalability and health/environmental impacts as important constraints on polymeric nanocomposite membranes, making retention and process simplicity part of the final performance assessment.

Conclusion and Discussion

The proposed methodology provides a structured way to evaluate advanced water purification membranes in which functionalized nanomaterials are treated as active components rather than passive fillers. By comparing an unmodified TFC membrane with GO-, TiO₂-, and GO/TiO₂-functionalized TFN membranes under the same fabrication controls and challenge conditions, the protocol can determine whether changes in flux, rejection, fouling, antibacterial behavior, and regeneration are directly associated with nanomaterial functionalization. The approach is consistent with the historical development of membrane nanotechnology from materials modification toward multifunctional treatment interfaces [2,3,14]. The most important methodological feature is balanced evaluation.

High permeance alone is not sufficient because the practical value of a membrane depends on selectivity, fouling resistance, chemical stability, and safe operation. GO can support hydrophilicity, nanoscale transport, and biofouling control [4,11,16], while TiO_2 can contribute hydrophilicity and photocatalytic regeneration. Their combination is therefore a reasonable hypothesis for multifunctional purification, but synergistic performance should not be assumed. Hybrid loading may also increase roughness, create agglomerates, or generate defects. Controlled fabrication and full surface characterization are necessary to distinguish real improvements from artifacts. The proposed results framework additionally prevents overstatement by requiring repeated filtration-cleaning cycles and explicit nanoparticle-leaching analysis. These criteria respond to the sustainability concerns raised for nano-enabled water treatment [9,17]. If experimentally validated, a stable hybrid nanocomposite membrane could be useful for advanced wastewater reuse, drinking-water polishing, industrial process-water treatment, or pretreatment before high-recovery desalination. Future studies should extend the protocol to real water matrices containing natural organic matter, competing ions, colloids, and microorganisms; perform longer pilot-scale testing; and include life-cycle cost and environmental impact. Emerging water-channel membranes and other nanoscale transport architectures reviewed by Lim et al. [15] may also be incorporated as future comparators. Overall, the framework converts broad claims about advanced nanomaterials into a reproducible set of measurable membrane-performance and safety criteria.

References

- M. A. Shannon, P. W. Bohn, M. Elimelech, J. G. Georgiadis, B. J. Mariñas, and A. M. Mayes, "Science and technology for water purification in the coming decades," *Nature*, vol. 452, no. 7185, pp. 301–310, 2008. DOI: 10.1038/nature06599.
- M. M. Pendergast and E. M. V. Hoek, "A review of water treatment membrane nanotechnologies," *Energy & Environmental Science*, vol. 4, no. 6, pp. 1946–1971, 2011. DOI: 10.1039/C0EE00541J.
- X. Qu, P. J. J. Alvarez, and Q. Li, "Applications of nanotechnology in water and wastewater treatment," *Water Research*, vol. 47, no. 12, pp. 3931–3946, 2013. DOI: 10.1016/j.watres.2012.09.058.
- J. Yin, G. Zhu, and B. Deng, "Graphene oxide enhanced polyamide thin-film nanocomposite membrane for water purification," *Desalination*, vol. 379, pp. 93–101, 2016. DOI: 10.1016/j.desal.2015.11.001.
- M. E. A. Ali, L. Wang, X. Wang, and X. Feng, "Thin film composite membranes embedded with graphene oxide for water desalination," *Desalination*, vol. 386, pp. 67–76, 2016. DOI: 10.1016/j.desal.2016.02.034.
- J. R. Werber, C. O. Osuji, and M. Elimelech, "Materials for next-generation desalination and water purification membranes," *Nature Reviews Materials*, vol. 1, art. 16018, 2016. DOI: 10.1038/natrevmats.2016.18.
- J. H. Jhaveri and Z. V. P. Murthy, "A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes," *Desalination*, vol. 379, pp. 137–154, 2016. DOI: 10.1016/j.desal.2015.11.009.
- C. Ursino, R. Castro-Muñoz, E. Drioli, L. Gzara, M. H. Albeirutty, and A. Figoli, "Progress of nanocomposite membranes for water treatment," *Membranes*, vol. 8, no. 2, art. 18, 2018. DOI: 10.3390/membranes8020018.
- M. S. Mauter, I. Zucker, F. Perreault, J. R. Werber, J.-H. Kim, and M. Elimelech, "The role of nanotechnology in tackling global water challenges," *Nature Sustainability*, vol. 1, no. 4, pp. 166–175, 2018. DOI: 10.1038/s41893-018-0046-8.
- Y. Wen, J. Yuan, X. Ma, S. Wang, and Y. Liu, "Polymeric nanocomposite membranes for water treatment: a review," *Environmental Chemistry Letters*, vol. 17, no. 4, pp. 1539–1551, 2019. DOI: 10.1007/s10311-019-00895-9.
- W. Cheng, X. Lu, M. Kaneda, W. Zhang, R. Bernstein, J. Ma, and M. Elimelech, "Graphene Oxide-Functionalized Membranes: The Importance of Nanosheet Surface Exposure for Biofouling Resistance," *Environmental Science & Technology*, vol. 54, no. 1, pp. 517–526, 2020. DOI: 10.1021/acs.est.9b05335.
- H. Chen, M. Huang, Y. Liu, L. Meng, and M. Ma, "Functionalized electrospun nanofiber membranes for water treatment: A review," *Science of the Total Environment*, vol. 739, art. 139944, 2020. DOI: 10.1016/j.scitotenv.2020.139944.

M. N. Pervez, M. Balakrishnan, S. W. Hasan, et al., "A critical review on nanomaterials membrane bioreactor (NMs-MBR) for wastewater treatment," *npj Clean Water*, vol. 3, art. 43, 2020. DOI: 10.1038/s41545-020-00090-2.

M. Khraisheh, S. Elhenawy, F. AlMomani, M. Al-Ghouti, M. K. Hassan, and B. H. Hameed, "Recent Progress on Nanomaterial-Based Membranes for Water Treatment," *Membranes*, vol. 11, no. 12, art. 995, 2021. DOI: 10.3390/membranes11120995.

Y. J. Lim, K. Goh, and R. Wang, "The coming of age of water channels for separation membranes: from biological to biomimetic to synthetic," *Chemical Society Reviews*, vol. 51, no. 11, pp. 4537–4582, 2022. DOI: 10.1039/D1CS01061A.

N. S. Lazarenko, V. V. Golovakhin, A. A. Shestakov, N. I. Lapekin, and A. G. Bannov, "Recent Advances on Membranes for Water Purification Based on Carbon Nanomaterials," *Membranes*, vol. 12, no. 10, art. 915, 2022. DOI: 10.3390/membranes12100915.

N. F. Al Harby, M. El-Batouti, and M. M. Elewa, "Prospects of Polymeric Nanocomposite Membranes for Water Purification and Scalability and their Health and Environmental Impacts: A Review," *Nanomaterials*, vol. 12, no. 20, art. 3637, 2022. DOI: 10.3390/nano12203637.