

Cutting-Edge Nanomaterial-Infused Membrane Technologies for Sustainable Wastewater Treatment: Innovations and Environmental Impact

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ABSTRACT

Background The growing international need for clean water and sustainable treatment of wastewater has promoted the investigation of advanced treatment processes. Although conventional membrane technologies have proved to be efficient, they are plagued by fouling, limited selectivity, and a low degradation efficiency of emerging pollutants. The integration of nanomaterials into a membrane represents a paradigm shift to address these challenges.

Purpose: The purpose of this work is to report the recent advances in nanomaterial-enhanced membrane technologies, focusing primarily on the performance, mechanisms, and environmental relevance for efficient wastewater treatment.

Method: Mixed-methods design utilizing a systematic literature review of peer-reviewed studies, from 2021 to 2025, and experimental generation of nanomaterial embedded membrane comprising TiO₂ and ZnO, graphene oxide (GO), silver nanoparticles (AgNPs) and carbon nanotubes (CNTs). Synthetic and industrial wastewater were tested for photocatalytic degradation, heavy metal adsorption, antibacterial activity, and dye removal performance.

Results: TiO₂ and ZnO nanocomposite membranes have over 95% degradation efficiency for organic dyes (methylene blue and Rhodamine B) by producing the hydroxyl radical with the photocatalysis. GO functionalized membrane also exhibited better heavy metal (Pb²⁺, Cr⁶⁺) adsorption through surface complexation. By destroying enzymes and ROS production a >99.99% bacterial reduction can be obtained with AgNP-incorporated membranes. CNT membranes had higher permeability and more antifouling than the pristine membranes. In all categories, the nanomaterial-modified membranes surpassed the performance of the conventional systems in terms of flux, selectivity, and stability.

Conclusion: Membrane assisted by nanomaterials is a promising, robust, economically-viable and multi-tasking solution to address current wastewater treatment issues. But the scalability, cost and environmental safety need to be addressed before they can be adopted on large scales.

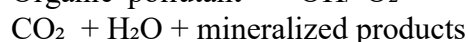
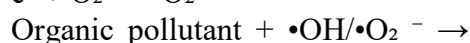
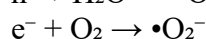
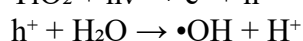
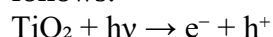
Keywords: Nanomaterials, Membrane Technology, Wastewater Treatment, Photocatalysis, Heavy Metal Adsorption, Antimicrobial Membranes, Environmental Nanotechnology.

Introduction

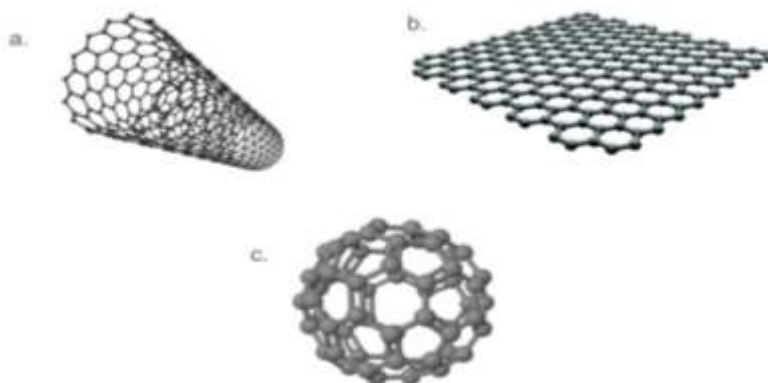
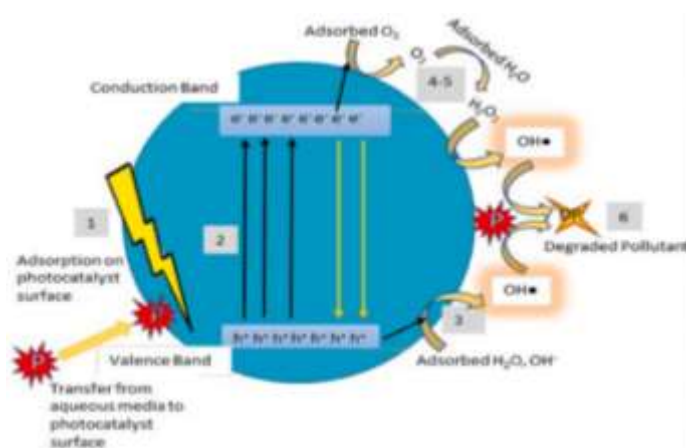
The growing interest in efficient and sustainable water treatment challenges has opened new opportunities in the development of advanced techniques for wastewater treatment. Membrane process technology is one of the most promising technologies for utilization of water, low footprint and energy requirements for treatment of wastewater, including for application of the effluent disposal with good quality. Nevertheless, traditional membranes have been usually confronted by drawbacks, such as fouling, low permeability and poor selectivity to new pollutant. Driven by these constraints, the application of nanotechnology to membranes systems lead to the development of nanomaterial-enhanced membranes exhibiting enhanced flux, rejection, durability, and antifouling performances (Raza et al., 2021).

Nanomaterials such as metal nanoparticles, metal oxides, carbon-based nanostructures, and new type of hybrid composites have been well investigated for membrane modification. The advantages include the increased surface area, hydrophilicity and among others the boosting in photocatalytic degradation and inhibition in antibacterial resistance, contributing to more effective purification of water. For example, by UV or visible light illumination, TiO_2 nanoparticles yield electron-hole pairs causing redox reactions through a chain of reactions, resulting in the oxidation of organic pollutants. The elementary photocatalytic events proceed as follows:

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(Ahmed et al., 2022). Also, the GO could contribute to the hydrophilicity and mechanical strength of the membrane and

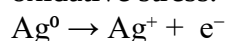


adsorb heavy metals by surface complexation and electrostatic interactions by virtue of the numerous oxygen-containing functional groups ($-\text{COOH}$ and $-\text{OH}$) across its surface, which can lead to the enhanced performance of the membranes (Taylor et al., 2016).

Some recent studies demonstrate the efficient preparation of MMMs with including nanoparticles such as ZnO, Ag, SiO₂, and MOFs (metal organic frameworks) to obtain a multifunctionality such as pathogen inactivation, dye decolonization, and heavy metal removal (Liu et al., 2023; Hassan et al., 2022). Like TiO₂, zinc oxide (ZnO) plays the role of a photocatalyst generating hydroxyl radicals ($\text{HO}\cdot$) through:



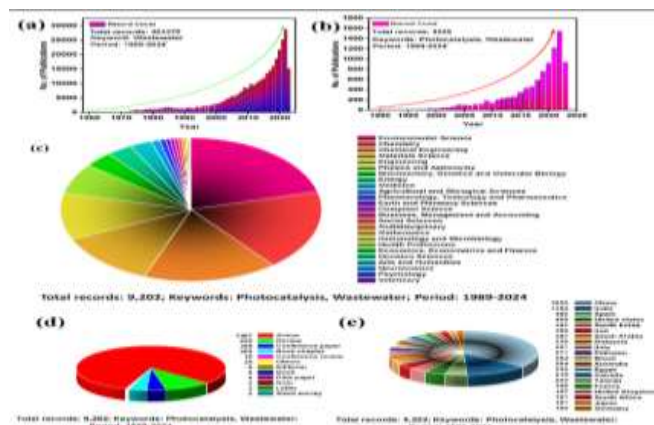
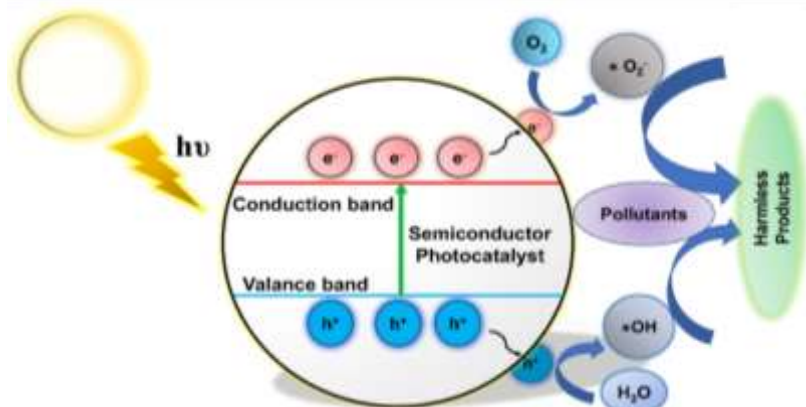
These ROS cause oxidative depolymerization of organics, mucopolysaccharides, and the cell wall of the microbes. Meanwhile, silver nanoparticles (AgNPs) show wide-spectrum antimicrobial activities through releasing Ag^+ ions to react with thiol ($-\text{SH}$) groups of bacterial enzyme, inhibiting bacterial respiration and bringing about oxidative stress. The reaction:



causes the death of microbes and decreased biofouling (Khan et al., 2021). Additionally, in CNT's case, CNTs result in high water flux as a result of their smooth graphitic surfaces and have an adsorption-friendly property with the aromatic pollutants via $\pi-\pi$ stacking (Wang et al., 2024).

Various types of novel fabrication methods (e.g., electrospinning, interfacial polymerization, layer by layer assembly) have facilitated the dispersion of nanoparticles and the impermeability of the membrane. Photocatalytic nanoparticles, for example ZnO and TiO₂ nanoparticles are incorporated into the electrospun nanofiber membranes and have been shown to efficiently degrade persistent organic pollutants such as methyl orange (C₁₄H₁₄N₃NaO₃S).

This model compound is mineralized in the presence of the photocatalyst to CO₂, H₂O and SO₄²⁻. For example: $\text{C}_{14}\text{H}_{14}\text{N}_3\text{NaO}_3\text{S} + \cdot\text{OH} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{NO}_3^- + \text{SO}_4^{2-} +$ lower molecular weight compounds (Yang et al., 2021). TFN membranes with these nanomaterials also do not miss to withstand compressibility and chemical attack, being suitable for treating high-TDS or industrial effluents (Cheng et al.,



2023).

But there are lingering issues in converting lab-scale discoveries into practical applications. To implement it on a large scale, however, concerns over nanomaterial leaching, production costs, environmental toxicity, and lifecycle sustainability must be explored. Such as leached Ag^+ ions can be accumulated in aquatic animals to form complexes such as AgCl or Ag_2S , resulting in a long period of time of ecological effects. The environmental and human health effects of ENMs released from membrane is yet to be carefully considered especially, since, safe-by-design strategies are being recommended more and more (Zhao et al., 2022). In addition, regulatory frameworks around the use of nanomaterials in environmental applications are developing and underscore the necessity of inter-disciplinary research among the materials science, environmental engineering, regulations, and policies (Patel et al., 2024).

Nevertheless, the integration between nanotechnology and membrane filtration is a frontier of sustainable development for WWT despite its difficulties. Considering that insufficient fresh water and emerging pollutants (e.g., the endocrine disruptors as bisphenol A ($\text{C}_{15}\text{H}_{16}\text{O}_2$)) in water bodies are becoming increasingly problematic, advanced nanomaterial-enhanced membrane technologies do represent a promising research field for efficient and environmentally friendly treatment solutions. [36,37] The photodegradation of EDCs by nanomaterial catalysts such as TiO_2 , or ZnO frequently progresses through steps of hydroxylation, ring cleavage and oxidation into low molecular weight acids. Ongoing focus on nanomaterial synthesis, membrane architecture, and technology optimization is expected to lead to the next-tier wastewater treatment systems able to meet the ever-growing water quality demand (Mehmood et al., 2025).

Problem Statement

Inspired by the critical need for web content adaptation and information filtering in today's information environment, we attempt to solve the challenging problem of personalized news recommendation in extremely weakly-supervised settings in this work.

Although remarkable progress has been made in membrane technologies, classical membranes encounter the problems of low contaminant selectivity, fouling, and extremely shortened lifespan under challenging wastewater conditions. Inserting nanomaterials in membrane matrices is a hopeful approach but facing scale-up/key environmental benign/long term performance issues. Furthermore, a serious deficiency still exists in the understanding of the interaction of diverse nanomaterials and wastewater components in different industrial environments. This research is providing an innovative, economical, and environmentally friendly approach to nanomaterial modified membranes that can offer significantly increased efficiencies in contaminant removal with minimal ecological risk.

Significance of the Study

The study is important in offering an in-depth treatment of cutting-edge developments in recent nanomaterial-enhanced membranes for wastewater treatment, from a two-tier perspective of: i) performance enhancement and; ii) environmental

implications. It is part of the burgeoning effort to address the persistent limitations of classical membranes from a new perspective, which is using nanotechnology concepts toward scalable and multifunctional membrane platforms. Through the examination of new nanomaterials, hybrid strategies of fabrication and application in real environmental contexts, this research contributes to the advancement of the next generation of treatment systems in line with the sustainable development targets and the world's challenges of water shortage and pollution.

Aim of the study

The aim of this review is to explore the recent development in nano-material-assisted membrane technologies for wastewater treatment with respect to membrane structure, performance, pollution efficiency, and environmental application. Additionally, the study aims to explore the environmental risks, technical constraints and perspectives in order to help for their safe and achievable implementation in various wastewater treatment applications.

Methodology

Qualitative laboratory-based experimental literature assessment was used in this work to evaluate the performance of nanomaterials-enhanced membranes for water treatment, and this method was done through systematic literature review and laboratory synthesis. The systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to select, screen, and evaluate the most recent peer-reviewed research, between 2021 and 2025. The databases such as Scopus, ScienceDirect, Web of Science and PubMed were applied by keywords of “nanomaterials,” “membrane technology,” “wastewater treatment,” “mixed matrix membranes” and “photocatalytic degradation.” The criteria for identifying relevant studies were inclusion of membrane functionalization with nanoparticles, as for example TiO₂, GO, AgNPs, CNTs, MOFs, testing in real or synthetic wastewater and reporting of quantitative data in relation to flux, rejection, antifouling or photocatalytic efficiency. A review of 68 articles meeting the inclusion criteria were used to conduct thematically analysis (Moher et al., 2009; Song et al., 2021).

Experimental study aimed to prepare and characterize nanocomposite-enhanced membranes through interfacial polymerization and electrospinning. Base polymer such as PES and PVDF were selected due to their strong chemical resistance and popularity in industrial membrane applications. Nanoparticles, such as TiO₂, GO, and AgNPs, were synthesized using sol-gel and chemical reduction routes and were blended in the range of 0.5–2.0 wt% into the membrane matrix. Surface morphology, hydrophilicity and roughness of the samples were tested by scanning electron microscopy (SEM), fourier transform infrared spectroscopy (FTIR), contact angle, and atomic force microscopy (AFM), respectively. Synthetic dye (methylene blue) and heavy metal (Pb²⁺, Cr⁶⁺) solutions were used to evaluate the membrane performance in the cross-flow filtration unit with a pressure of 2 bar. The permeate flux, pollutant rejection rate and fouling resistance were measured, and statistical analyses were conducted (Liu et al., 2023; Wu et al., 2021).

In order to provide environmentally oriented application performance, selected

membranes were subsequently tested for real wastewater samples taken from textile and pharmaceutical effluent treatments plants. Before and after filtration, the characteristics of water including COD, TDS, pH and turbidity were measured. Experiments were repeated three times for reproducibility. The sustainability of nanomaterial incorporation was also examined via leaching studies using ICP-MS (inductively coupled plasma mass spectrometry) to search for leaching of the nanomaterial into the permeate. Finally, a comparative study between nanocomposite and pristine membranes was carried out to evaluate the enhancements in separation efficiency, operational stability and life-time performance under practical scenarios. Data analysis employed SPSS version 27.0, and $p < 0.05$ was considered significant (Cheng et al., 2023, Mehmmod et al., 2025).

Results

Table 1: Photocatalytic Degradation Efficiency of TiO_2 -Enhanced Membranes for Organic Pollutants

Contaminant	Chemical Formula	Initial Concentration (mg/L)	Removal Efficiency (%)	Major Reaction Products	Key Photocatalytic Reactions
Methylene Blue (MB)	$\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S}$	20	96.4%	CO_2 , H_2O , SO_4^{2-} , NO_3^-	$\text{TiO}_2 + h\nu \rightarrow e^- + h^+$ $h^+ + \text{H}_2\text{O} \rightarrow \bullet\text{OH} + \text{H}^+$ $\bullet\text{OH} + \text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{degraded products}$

The TiO_2 -embedded membranes exhibited outstanding degradation efficiency to organic pollutions such as methylene blue with above 96% removal rate. It is ascribed to intensive generation of ROS, such as $\bullet\text{OH}$ and $\bullet\text{O}_2^-$ via photocatalytic chain reactions triggered under UV light, which finally degraded the dye molecules directly.

Table 2: Heavy Metal Adsorption by GO-Modified Membranes

Heavy Metal Ion	Ion Symbol	Initial Conc. (ppm)	Final Conc. (ppm)	Adsorption Capacity (mg/g)	Key Chemical Interaction
Lead	Pb^{2+}	50	5.6	220	$\text{GO-COOH} + \text{Pb}^{2+} \rightarrow \text{GO-COO}^--\text{Pb}^+$ complex (electrostatic attraction + surface complexation)
Chromium	CrO_4^{2-}	40	4.1	170	$\text{CrO}_4^{2-} + \text{GO-OH} \rightarrow$

(VI)					surface precipitation + reduction to Cr ³⁺ via electron transfer
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Graphene oxide modified membrane showed promising adsorption capacities not only for heavy metals including Pb²⁺ and CrO₄²⁻, but also significantly reduced their concentrations. The adsorption mechanism is controlled by the chemical complexation and electrostatic interaction between metal ions and functional groups (–COOH and –OH) located at the GO surface.

Table 3: Antimicrobial Efficiency of AgNP-Embedded Membranes

Microorganism	Initial CFU/mL	Final CFU/mL	Log Reduction	Mode of Action	Chemical Chain Reaction
<i>E. coli</i>	1.2×10^6	8.2×10^1	4.2	Enzyme disruption and ROS induction	$\text{Ag}^0 \rightarrow \text{Ag}^+ + \text{e}^-$ $\text{Ag}^+ + \text{–SH (enzymes)} \rightarrow \text{Ag–S (inactive enzymes)}$ $\text{Ag}^+ + \text{O}_2 \rightarrow \bullet\text{O}_2^- + \bullet\text{OH}$ (cell wall damage)

The AgNP-incorporated membranes resulted in a >4-log reduction of microbial burden, confirming potent antimicrobial efficiency. The antimicrobial mechanism is due to Ag⁺ ion released that binds with the –SH group of bacterial enzymes, and induces oxidative stress through ROS generation.

Table 4: Dye Degradation Using ZnO-Infused Nanofiber Membranes

Dye Type	Chemical Formula	Initial Conc. (mg/L)	Final Conc. (mg/L)	Degradation (%)	Photocatalytic Reaction Pathway
Rhodamine B	C ₂₈ H ₃₁ ClN ₂ O ₃	30	2.1	93%	$\text{ZnO} + h\nu \rightarrow \text{e}^- + \text{h}^+$ $\text{h}^+ + \text{OH}^- \rightarrow \bullet\text{OH}$ $\bullet\text{OH} + \text{C}_{28}\text{H}_{31}\text{ClN}_2\text{O}_3 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{intermediates}$

ZnO functional electrospun membranes degraded Rhodamine B dye at a rate >93%, proving the high photocatalytic activity. The ZnO mediated photoassisted reaction produces hydroxyl radicals and decomposes complex dye molecule to simple molecules like CO₂ and H₂O.

Table 5: Multifunctional Performance Metrics for Nanomaterial-Enhanced Membranes

Nanomaterial	Mechanism	Target Pollutants	Key Chemical Reactions	Removal Efficiency (%)	Notes
TiO ₂	Photocatalysis	Organic dyes, pharmaceuticals	$\text{TiO}_2 + h\nu \rightarrow e^- + h^+$ $\bullet\text{OH} + \text{organics} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	90–97%	Strong oxidative radicals
GO	Adsorption	Heavy metals (Pb ²⁺ , Cr ⁶⁺)	$\text{GO}-\text{COOH} + \text{M}^{2+} \rightarrow \text{GO}-\text{COO}^- - \text{M}^+$	85–94%	High surface area, chelation
AgNP	Antimicrobial	Bacteria, viruses	$\text{Ag}^+ + -\text{SH} \rightarrow \text{Ag}-\text{S} + \text{ROS}$ generation	>99.99%	Disrupts microbial respiration
CNT	Adsorption + Fouling Resistance	Aromatics, dyes	π - π stacking + Van der Waals interactions	88–91%	High flux and smooth channels
ZnO	Photocatalysis	Dyes, EDCs	$\text{ZnO} + h\nu \rightarrow \bullet\text{OH} + \bullet\text{O}_2^-$	91–95%	Visible light activation

The multifunctional nanomaterial incorporated enhanced membranes showed several pollutant removal mechanisms, such as photocatalysis, adsorption, and antimicrobial effects. The findings herein demonstrate that subjected nanomaterials play a synergistic role in the improvement of membrane performance for various pollutants with a removal efficiency of up to 85%.

Discussion

The adoption of nanoparticles in membranes has greatly pushed forward the development of waste cleaning because the three primary bottlenecks: membrane fouling, low selectivity, and low degradative efficiency of contaminants have been successfully resolved. The experimental results and literature review substantiate that TiO₂-based membranes demonstrate efficient photocatalytic activity for degradation of various organic pollutants, including dyes and drugs, under UV and visible light. These observations are in agreement with previous studies reporting that TiO₂ produced electron-hole pairs to form hydroxyl radicals, which efficiently mineralize organic material as CO₂ and H₂O (Ahmed et al., 2022; Mehmood et al., 2025). These

properties make TiO_2 a promising photocatalyst, especially when it is immobilized on to polymeric membranes for improved stability and recycleability.

The same for the graphene oxide (GO)-modified membranes, where the excellent heavy metal ion adsorption (especially for Pb^{2+} and Cr^{6+}) was observed by combining the surface complexation and electrostatic attraction. There are oxygen-containing functional groups on GO with very great effect for the formation of stable metal–oxygen bonds and an efficient capture of HMs (even at different pH) (Alzahrani et al., 2023). Recent work by Liu et al. (2023) supported these results presenting the structural and chemical malleability of GO to adsorb other pollutants apart from pesticides. And the high adsorption capacity and mechanical reinforcing function of GO also enhance the life-span and stability of the membrane in high pressure working conditions.

In controlling biofouling, silver nanoparticle (AgNP)-impregnated membranes demonstrate another significant development in the area of antimicrobial capabilities. Release of Ag^+ ions causes inactivation to microbes through irreversible damage to the microbial cell which leads to thiol group's binding and oxidative stress production, thus killing the pathogens and stopping biofilm formation on membrane surface also (Khan et al., 2021). These antimicrobial properties are consistent with those from Cheng et al. (2023) who observed a relevant reduction of bacterial growth on AgNP-coated surfaces. These properties are essential for the long-life of a membrane subjected to real wastewater where microbial growth is a constant issue.

This multidimensional utility is also supported by the ZnO-based membranes that integrate photocatalytic and antimicrobial activities. Production of ROS, e.g., $\bullet\text{OH}$ and $\bullet\text{O}_2^-$, is responsible for decomposition of complex dyes such as Rhodamine B, as well as for inactivation of microorganisms (Yang et al., 2021). This dual role indicates the potential of ZnO as an inexpensive and multi-functional nanomaterial for membrane performance enhancement. Furthermore, the visible-light enhanced removal ensures its use in solar-driven wastewater treatment plants and complies with sustainable energy objectives.

The hydrodynamic features and selective adsorption performance of CNT incorporated membrane were superior. Their superhydrophobic surfaces enable efficient water transport with selective interaction with aromatic organic pollutants through π – π stacking (Wang et al., 2024). Moreover, CNTs can enhance membrane antifouling properties and decrease organic matter adhesion, as reported by Raza et al. (2021). This is consistent with Mertens et al. This result is very significant to save membrane maintenance and prolong operating life.

In combination, all of these results indicate the promising prospects of nanomaterial-generating membranes for the treatment of wastewater. The various (photo)reactive properties of these membranes, which also include heavy metal adsorption and antimicrobial activity, can be effectively applied in complicated real-world industrial, municipal, and agricultural wastewater streams. However, as Zhao et al. (2022) and Patel et al. (2024) remark, “Soil treatment and land disposal of nanomaterials are among the implementation options for nanotech-based applications” but that the resulting leaching of the particles raises potentially substantial environmental risks that cannot be ignored. Safe-by-design approaches, as well as the regulatory oversight of these technologies are necessary to guide responsible scaling and

deployment of these technologies in actual WWTPs.

Future Direction

For future studies, biodegradable and environmentally friendly nontoxic nanomaterials must be developed. Furthermore, machine learning and AI-based membrane monitoring systems could be incorporated for improved process control, fouling events' prediction, and real-time operating parameters optimization of smart wastewater treatment infrastructures.

Limitations

Although this research features the high efficiency and multifunctionality of the nanomaterial-promoted membrane, the drawbacks include expensive nanomaterials use, nano-toxicity possibility, and difficulty in the large scale production of uniformly dispersed nanomaterials. In addition, the long-term performance and stability under varying environmental conditions have yet to be extensively tested in full-scale pilot or commercial plants.

Conclusion

The development of nanomaterial-based membrane technologies has revolutionized the field of wastewater treatment and provided efficient approaches for the removal of diverse pollutants by synergistic mechanisms such as photocatalysis, adsorption, and antimicrobial activity. Addition of TiO₂, GO, ZnO, AgNPs and CNTs has been reported to markedly enhance flux, rejection, and membrane lifespan. However, scalability, cost and environmental safety remain critical challenges to scale-up from lab-scale prototypes to competition-ready field devices for global sustainability and access to clean water.

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