Theory and Practice of Science and Technology
2025, VOL. 6, NO. 11, 61-65
DOI: 10.47297/taposatWSP2633-456912.20250611

Janus Membranes and Graphene-based Membranes in Water Treatment: A Comparative Study

Haoliang Liu

Environmental Engineering, Beijing Jiaotong University,Beijing, 264401, China

ABSTRACT
Human existence and progress are inherently dependent on water. However, with the acceleration of globalization, industrialization, and population expansion, water scarcity and contamination are worsening. Janus membranes, distinguished by their asymmetric structure and unique chemical composition, demonstrate exceptional performance in liquid unidirectional permeation, oil-water separation, seawater desalination, and micro-pollutant removal. Graphene-based membranes, conversely, demonstrate exceptional efficacy in contaminant removal—they are proficient at eliminating organic compounds, heavy metal ions, and microorganisms due to their extensive specific surface area and chemical characteristics. This paper focuses on the preparation techniques, modification methods, and innovative design processes of Janus membranes, while conducting a comparative analysis of their application effects in seawater desalination and wastewater treatment compared to graphene-based membranes. Additionally, the study systematically reviews the prospects, challenges, and future development directions of graphene technology applications in Janus membrane design.

KEYWORDS
Janus membrane; Graphene-based Membranes; Water treatment; Preparations methods; Global water scarcity

1 Introduction

1.1 Research Background and Significance

Water is essential for human survival and development. Yet, as globalization picks up pace, and industrialization and population growth surge, the issues of water scarcity and water contamination are intensifying [1]. Lately, specific organic substances and heavy metal ions, even in small amounts, are posing tough problems for our environment and can mess with our health for a long time [2]. Old-school water cleaning ways like letting stuff settle, running it through filters, or boiling it to get the water out of the mix do help make water better. But when it comes to tricky, complicated gunk, they usually don't cut it. Janus membranes and graphene-based membranes have emerged as promising water treatment technologies, attracting significant attention owing to their distinctive structural configurations and exceptional performance attributes.

1.2 Research Status of Membrane Technologies

Janus membranes, with their lopsided build and mixed-up chemistry, are pretty handy for stuff like letting liquids pass one way, separating oil from water, turning seawater into freshwater, and getting rid of tiny pollutants [3]. Membranes made from graphene are super good at pulling out organic junk, metal bits, and tiny living things from water [4]. The reason behind this lies in their elevated specific surface area, sturdy mechanical attributes, and tailorable chemical traits. This study aims to conduct an in-depth comparative assessment of these two membrane types in the context of water purification, examining their respective strengths, limitations, and applicable scenarios. While graphene-based membranes have demonstrated encouraging results in aquatic remediation, Janus membranes have displayed unique advantages including durability and adaptability through leveraging diverse functional properties in water treatment processes.

1.3 Research Objectives and Contents

In the past of years, some papers have reported the excellent performance of Janus membrane and graphene-based membranes. Janus is the name of the ancient Roman god with two faces, each looking in opposite directions—one towards the past and the other towards the future .In the field of materials science, the term Janus was first coined by De Gennes for the synthesis of particles that are chemically distinct on each hemisphere [5]. The first Janus materials were composed of poly(methyl methacrylate) and polystyrene. Accordingly, materials with ambivalent properties are called Janus, such as Janus particles, Janus nanosheets, and Janus membranes. The Janus membrane was first introduced by Cheng and Wiersma in 1982, and since then, the number of research studies focused on improvement methods for Janus membranes has drastically increased. . More recently, a number of review articles have surfaced in this field, mainly concentrating on the treatment of graphene-based membranes, especially those containing GO, and their unique uses, including molecular separation driven by pressure, barrier films that are impervious, and the process of desalination.

Although the extensive body of existing literature, research on Janus membranes and graphene-based membranes has reached a stage where strategic updates are necessary to encompass the latest advancements, emerging trends, and opportunities[Table 1]. This paper compares Janus membranes with graphene-based membranes in water treatment applications, examining their preparation methods, structural characteristics, mass transfer mechanisms, and potential applications. It highlights the potential of these advanced membrane technologies to enhance water treatment efficiency and environmental sustainability, while discussing their role in addressing global water scarcity and pollution challenges. The study also identifies opportunities and challenges in practical implementation, along with projections for future development directions.

Table 1 Janus Membrane-Photolysis,Janus Membrane-Plasma Treatment,Graphene-based film-CVD method, Graphene-based membrane-redox method

Preparation cost	Operational condition	Scale production potential	Energy consumption level	Core advantage	Main limitations
Janus Membrane-Photolysis	Ultraviolet irradiation	High	Low	Low cost and simple process	Limited precision of function control
Janus Membrane-Plasma Treatment	Vacuum environment, precise parameter control	Middle	Middle	Highly controllable	High equipment maintenance costs
Graphene-based film-CVD method	High temperature (800-1000℃), inert gas	Middle	High	High purity	The equipment is expensive and requires a copper foil substrate
Graphene-based membrane-redox method	Strong acid oxidation, chemical reduction (room temperature)	High	Middle	Introduced and modified flexibly	More membrane defects and r egeneration requires chemical reagents

2 Overview of Membrane Technologies

2.1 Structural Characteristics of Janus Membranes

The The optimal thickness of Janus membranes is generally determined by design specifications. Research indicates that when the porosity in hydrophobic regions exceeds 70% and thermal conductivity ranges between 0.1 to 0.3 W/mK, the optimal thickness falls within 30-60 μm [6]. However, most practical hydrophobic membranes are typically controlled at 100-150 μm to compensate for their relatively weaker mechanical strength. For graphene-based membranes, the sp^2 hybridized carbon atoms are arranged in a honeycomb lattice. This seemingly simple structure produces many unexpected properties, involving electronic, mechanical, and thermodynamic fields, and has aroused great research interest worldwide [7].

2.2 Structural Characteristics of Graphene-Based Membranes

Graphene-based membranes, with their high specific surface area and tunable chemical properties, can achieve efficient separation and fouling resistance when properly designed. The integration of functional groups and nanomaterials on the graphene surface offers unique selective permeability and adsorption capabilities for these membranes . When in contact with various types of pollutants such as organic compounds, heavy metal ions, or microorganisms, graphene membranes may potentially enhance the removal efficiency of these contaminants compared to other membranes[Table 1]. For instance, graphene oxide membranes with abundant hydrophilic groups can effectively capture and retain water-soluble pollutants, while chemically reduced graphene membranes can selectively filter out specific ions and molecules due to their tailored pore structures. However, the stability and regeneration of graphene membranes remain challenges that need to be addressed.

3 Comparison of Membrane Preparation Methods

3.1 Janus Membrane Preparation Methods

Making Janus membranes uses different tricks. Usual ones are photolysis, plasma treatment, chemical grafting, and electro-induced methods.Photolysis uses UV light to make one side of the membrane like water and the other side hate water. It's easy, cheap, and great for making a lot of membranes. Plasma treatment lets you fine-tune the membrane's surface chemistry, giving you super precise control over tiny spots. This method is a game-changer for crafting Janus membranes. Chemical grafting puts water-loving and water-hating stuff on both sides of the membrane. With self-activated photo-grouting tech, it makes the membrane have different functions.This is now the main way to make Janus membranes. Electro-induced approaches construct electroactive surface interfaces on membrane surfaces via electrochemical polymerization, facilitating reversible dual-polarity modulation triggered by electrical signals for targeted and high-efficiency pollutant elimination.

3.2 Graphene-based Membrane Preparation Methods

Various methods exist for preparing graphene-based films, with common techniques including chemical vapor deposition (CVD), redox methods, and electrochemical modification.CVD enables the growth of graphene films on copper foil, allowing both large-area production of high-quality graphene films and performance optimization through controlled growth conditions. The redox method oxidizes graphite into graphene oxide, which is then chemically reduced back to graphene—A process that incorporates a multitude of functional groups to augment hydrophilicity and adsorption capacity [8]. Electrochemical modification introduces specific functional groups or nanomaterials onto graphene surfaces, thereby improving its adsorption and selective separation capabilities for particular pollutants. Janus membranes can also effectively regulate surface properties through photolysis and plasma treatment.

3.3 Comparative Analysis of Preparation Process of Janus Membrane and Graphene-based Membrane

But making graphene membranes with CVD is held back by pricey machines,keeping it from being used everywhere. Electrochemical tweaking can change membranes fast,but tricky reactions and fiddly settings make it hard to pull off.Also, the usual way to make graphene-based membranes,like some store-bought graphene sheets,needs super-high heat over 2800℃ and massive pressure above 200MPa.This calls for top-notch gear and uses a ton of energy,which shoots up the cost [9]. Using redox tricks and electrochemical tweaks really pumps up graphene's ability to grab stuff by adding defects and functional groups. But getting these materials back to a usable state might need fancy chemicals or complicated steps.Right now,we're using electrospinning to make Janus nanofiber membranes.The water-loving layer's got carbon black(CB) and polyvinyl alcohol(PVA) as its heat-grabbing layers, while the water-hating layer's made of polytetrafluoroethylene(PTFE) nanofibers.This method's the cheapest way to make top-notch Janus membranes. All in all, the many ways to make Janus and graphene-based membranes give us lots of options for cleaning water.These methods not only make the membranes better but also set the stage for new water treatment ideas. If we can make Janus membranes with higher precision,lower cost,and more stable methods, it'll be a big win for making them work better and last longer.

4 Comparison of Water Treatment Performance

4.1 Performance Comparison of Graphene-based Membrane and Janus Membrane in Water Treatment

Within the domain of aquatic remediation, Janus membranes possess distinct superiority compared to graphene-based membranes in terms of contaminant retention performance. For oil-water partitioning applications, Janus membranes attain a separation efficiency of over 99 percent; in marine water desalination processes, they exhibit a permeability coefficient up to 2.2×10^{-5} L/(m^2hPa), with a reverse salt flux as minimal as 0.007 g/L. Furthermore, Janus membranes demonstrate exceptional efficacy in eliminating microcontaminants—during initial water treatment trials, they accomplish almost total elimination via a one-step filtration procedure, simultaneously boasting elevated water flux and reduced energy expenditure [10].While graphene-based membranes are great at taking out organic junk,heavy metals, and tiny living things,they don't do as well with tricky micropollutants compared to Janus membranes[Fig.1].This means we need to tweak graphene-based membranes using other methods.The lopsided structure of Janus membranes gives them an edge in keeping gunk from building up. For example, in oil-water separation, the water-loving side of Janus membranes can stop oil droplets from sticking.This keeps the membrane surface clean and makes it last longer.Janus membranes can be zapped with electricity to get rid of the yucky stuff they've soaked up,which helps them last longer. Graphene-based membranes are also pretty good at keeping gunk from sticking,but getting them back in shape might need fancy chemicals or tricky steps,which costs more.For example,graphene oxide(GO) membranes get puffy in water. This makes the layers spread out,and they don't pick out ions as well.This swelling messes up the tiny squeeze effect the membrane is supposed to have,so it doesn't hold on to ions as much.

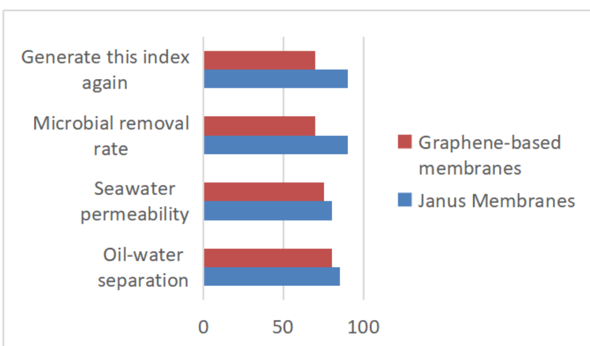

Figure 1 Water Treatment Performance Comparison Bar Chart

4.2 Cost analysis of Graphene-based Membrane and Janus Membrane in Water Treatment

When you look at the money side,Janus membranes cost a bit more to make than graphene-based ones.But because Janus membranes last longer and need less fixing,the money you spend at the start can be worth it in the long run [11]. Equally noteworthy is the fact that the manufacturing expenses associated with graphene-based membranes are notably high, especially considering the economic and operational stability constraints of existing industrial fabrication processes, which pose persistent hurdles that remain to be addressed [12]. To sum up, both Janus membranes and graphene-based membranes have a lot of potential for cleaning water. Graphene-based membranes are good at getting rid of lots of different pollutants. Janus membranes are special because they're great at separating oil from water, turning seawater into freshwater, and getting rid of tiny pollutants.

4.3 Long-Term Operational Stability

Looking ahead, Janus membrane materials are poised to assume a more pivotal role in a broader spectrum of water treatment applications, delivering more efficient and eco-friendly solution [13]. With ongoing technological progress and further cost reductions, Janus membranes are poised to emerge as the preferred material for a growing array of water treatment applications [14]. Against the backdrop of the growing urgency of water pollution issues, Janus membranes' exceptional separation efficiency and regenerative capabilities can provide strong support for achieving sustainable water resource management goals.

5 Exploration of Future Development Direction of Graphene-based Membrane and Janus Membrane

Looking ahead, the evolution of Janus membranes and graphene-based membranes will center on technical breakthroughs to boost operational efficiency and cut down on expenses. Specifically for Janus membranes, scholarly efforts are likely to prioritize more streamlined and budget-friendly fabrication techniques to engineer asymmetric architectures and functionalized surfaces. Crafting Janus membranes with elevated water permeability and reduced reverse salt diffusion can markedly enhance the efficacy of seawater desalination processes [15]. Thanks to their distinctive architectural design, Janus membranes enable precise partitioning of water molecules from salt ions in the filtration process, thereby facilitating enhanced water permeability and reduced salt passage during seawater desalination operations. This makes Janus membranes more efficient than graphene-based membranes [16]. This top-notch membrane material not only boosts the overall efficiency of seawater desalination systems but also cuts down on energy waste and environmental pollution. This paves the way for broader use of Janus membranes in water treatment. By fine-tuning the preparation process and material selection for Janus membranes, their stability in real-world applications can be significantly enhanced. This offers a practical technical solution to tackle global water scarcity [17]. This might mean checking out new materials and ways to make membranes to make them last longer and pick out stuff better, while also making them easier and cheaper to produce. For graphene-based membranes, researchers will work on tweaking the surface and adding functions to make them better at getting rid of a wider range of pollutants. This may entail developing novel functional moieties and nanoscale materials to enhance graphene's adsorption and separation capabilities. An encouraging future avenue involves integrating Janus membranes and graphene-based membranes with other water treatment technologies. This could include coupling these membranes with advanced oxidation processes, biological treatment systems, or alternative membrane-based technologies to construct hybrid systems that leverage the unique advantages of each component. These integrated systems can deliver superior performance in pollutant removal, energy conservation, and overall water quality improvement. As an example, merging Janus membranes with reverse osmosis systems can produce a more efficient and environmentally friendly method for desalination, whereas pairing graphene-based membranes with biofilters can enhance the removal of organic micropollutants and improve the overall effectiveness of water treatment procedures. With the advancement of urbanization and industrial transformation, the environmental compatibility and economic viability of water treatment technologies will serve as critical determinants for their widespread adoption and practical deployment [18]. Both Janus membranes and graphene-based membranes can help create more sustainable water treatment solutions. But it's crucial to dig deeper and fine-tune their life cycle assessments to cut down on environmental impact. This means looking at the energy used, materials needed, and waste created during the production, operation, and disposal of these membranes. All these factors play into the cost of the membranes and how well they perform. On top of that, we need to work on developing more cost-effective and scalable production methods. This will make membrane technology more accessible and economically useful, especially in many developed countries where water shortages and pollution issues are most severe. Ultimately, the primary goal of developing and optimizing Janus membrane and graphene-based membrane technologies is to tackle the urgent worldwide issues of water scarcity and contamination. By boosting the functional efficiency and purification performance of water treatment processes, these membranes act as a key remedy for providing pure and secure drinking water to millions of people without access today. Furthermore, they aid in sustainable water resource governance by facilitating the recovery and reuse of water in various industrial and agricultural contexts [19]. Janus membranes are set to make a big splash in water treatment, thanks to their effectiveness and affordability. What's more, the progress in these cutting-edge membrane technologies can greatly boost public health. By cutting down on waterborne diseases and giving us better water quality overall[Fig. 2] Given this situation, working together across borders and sharing knowledge are key to speeding up the use of these technologies all over the world. Since looking after the environment is a worldwide worry, Janus membranes are bound to make big strides in the future.

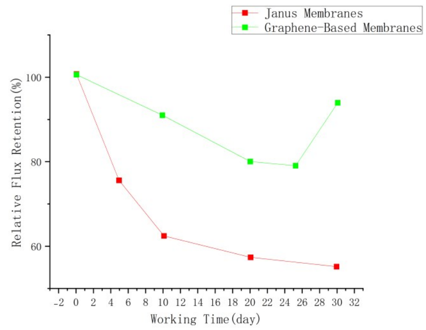

Figure 2 Comparison of long-term operation stability of two membranes

6 Janus Membrane and Graphene-based Membrane are the Cutting-edge Technological Advances in Water Treatment

In summary, Janus membranes and graphene-based membranes stand as representative advancements in state-of-the-art water treatment technologies.Each membrane type has its own good points and places where it can be used,but they also have their own problems to solve. Janus membranes, with their special one-sided design and ability to be refreshed with electricity,offer a good and long-lasting solution for many different water treatment needs.They offer new ideas and methods for solving water treatment problems.Meanwhile,Janus membranes have a strong ability to handle population-related and environmental protection challenges.With ongoing research and innovation progress in related fields, it is clear that combining these cutting-edge membrane technologies with alternative water treatment approaches is crucial. Additionally, refining their manufacturing procedures will serve as core priorities and promising directions. Such initiatives will lay the groundwork for developing more efficient, eco-friendly, and cost-effective water treatment strategies, ultimately contributing to societal and environmental well-being.

References

[1] Ding, D., Mao, H., Chen, X., Qiu, M., & Fan, Y. (2018). Underwater superoleophobic-underoil superhydrophobic Janus ceramic membrane with its switchable separation in oil/water emulsions. Journal of Membrane Science , 565 , 303–310.

[2] Zhang, W., Li, X., Qu, R., Liu, Y., Wei, Y., & Feng, L. (2019). Janus membrane decorated via a versatile immersion-spray route: Controllable stabilized oil/water emulsion separation satisfying industrial emission and purification criteria. Journal of Materials Chemistry A, 7, 4941–4949.

[3] Huang, Y. X., Wang, Z. X., Jin, J., et al. (2017). Novel Janus membrane for membrane distillation with simultaneous fouling and wetting resistance. Environmental Science & Technology ,51 (22), 13304–13310.

[4] Leong, Z. Y., Lu, G., & Yang, H. Y. (2019). Three-dimensional graphene oxide and polyvinyl alcohol composites as structured activated carbons for capacitive desalination. Desalination , 451 , 172–181.

[5] Liu, L., Lan, H., Cui, Y., Tang, Q., Bai, J., An, X., Sun, M., Liu, H., & Qu, J. (2024). A Janus membrane with electro-induced multi-affinity interfaces for high-efficiency water purification. Science Advances , 10 (21), eadn8696.

[6] Zhou, H., & Guo, Z. (2019). Superwetting Janus membranes: Focusing on unidirectional transport behaviors and multiple applications. Journal of Materials Chemistry A, 7, 12921.

[7] Moon, J.-Y., et al. (2020). Layer-engineered large-area exfoliation of graphene. Science Advances , 6 , eabc6601.

[8] Feng, D., Chen, Y., Wang, Z., & Lin, S. (2021). Janus membrane with a dense hydrophilic surface layer for robust fouling and wetting resistance in membrane distillation: New insights into wetting resistance. Environmental Science & Technology , 55 (20), 14156–14164.

[9] Zhang, Y., et al. (2012). Graphene oxide films: Preparation, properties, and applications. Chemical Reviews , 112 (11), 6150–6163.

[10] Wang, C., Ma, Z., Qiu, Y., Wang, C., Ren, L. F., Shen, J., & Shao, J. (2023). Patterned dense Janus membranes with simultaneously robust fouling, wetting and scaling resistance for membrane distillation. Water Research , 242 , 120308.

[11] Chen, Y., Lu, K. J., Japip, S., & Chung, T. S. (2020). Can composite Janus membranes with an ultrathin dense hydrophilic layer resist wetting in membrane distillation? Environmental Science & Technology , 54 (19), 12713–12722.

[12] Chen, X. F., Qiu, M. H., Ding, H., et al. (2016). A reduced graphene oxide nanofiltration membrane intercalated by well-dispersed carbon nanotubes for drinking water purification. Nanoscale , 8 , 5696–5705.

[13] Luo, D., Wang, F., Vu, B., et al. (2018). Synthesis of graphene-based amphiphilic Janus nanosheets via manipulation of hydrogen bonding. Carbon , 126 , 105–110.

[14] Guo, Y., & Wang, S. (2022). Graphene-based membranes for water purification: A review. Desalination , 523 , 15–26.

[15] Zhang, P., Gong, J. L., Zeng, G. M., et al. (2017). Cross-linking to prepare composite graphene oxide-framework membranes with high-flux for dyes and heavy metal ions removal. Chemical Engineering Journal , 322 , 657–666.

[16] Neves, T. D., Camparotto, N. G., Rodrigues, E. A., et al. (2022). New graphene oxide-safranin modified@polyacrylonitrile membranes for removal of emerging contaminants: The role of chemical and morphological features. Chemical Engineering Journal , 446 , 137176.

[17] Guo, Z., et al. (2023). Growth of low-defect nitrogen-doped graphene film using condensation-assisted chemical vapor deposition method. Materials (Basel) , 16 (1), 1–12.

[18] Sun, P. Z., Wang, K. L., & Zhu, H. W. (2016). Recent developments in graphene-based membranes: Structure, mass-transport mechanism and potential applications. Advanced Materials , 28 , 2287–2310.

[19] Li, X., Cai, W., An, J., Kim, S., Nah, J., Yang, D., & Ruoff, R. S. (2009). Large-area synthesis of high-quality and uniform graphene films on copper foils. Science , 324 (5932), 1312–1314.