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The Promise of Graphene: Advancing Water Desalination with Innovative Graphene Based Membranes

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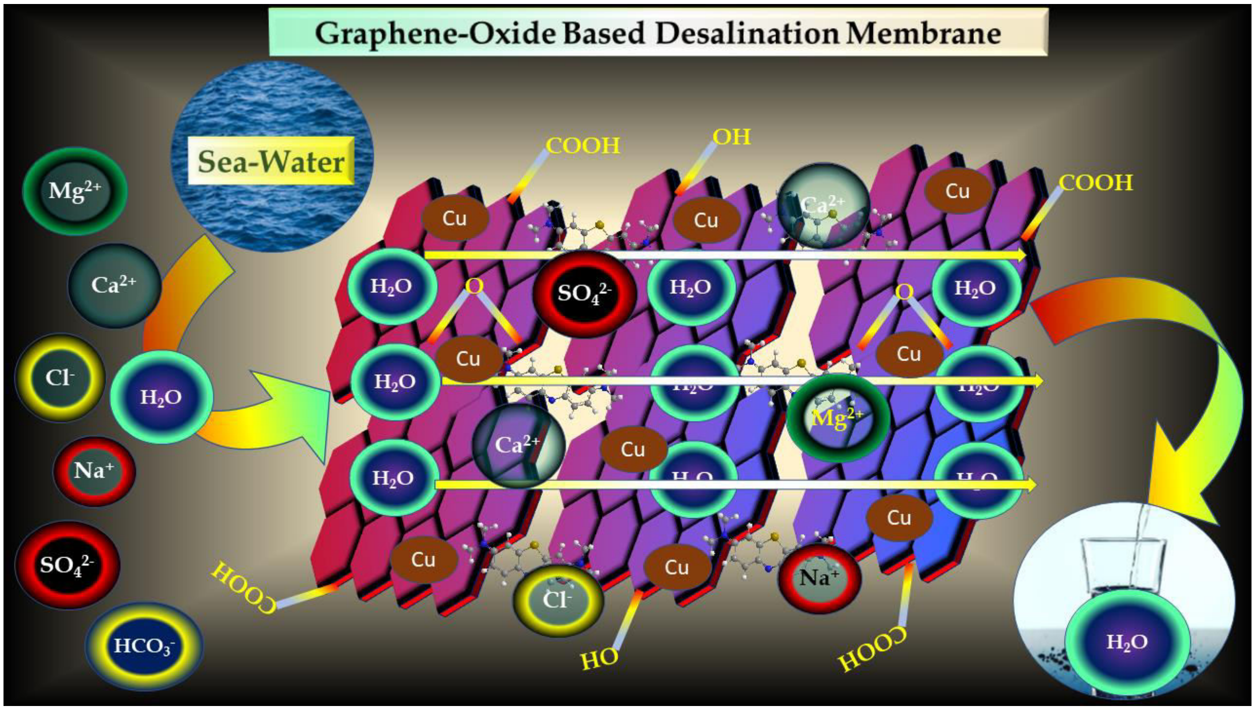
Abstract:
Water scarcity is a critical global challenge that demands innovative solutions. As populations grow and climate change intensifies, the need for efficient and sustainable water desalination technologies becomes increasingly pressing. In recent years, graphene-based membranes have emerged as a promising avenue for revolutionizing water desalination processes. This review article, titled "The Promise of Graphene: Advancing Water Desalination with Innovative Membranes," explores the vast potential of graphene-based membranes in addressing the world's freshwater shortage. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, possesses remarkable properties, including exceptional mechanical strength, high thermal and electrical conductivity, and impermeability to gases and liquids. These attributes make it an ideal candidate for membrane materials. In the context of water desalination, graphene membranes offer several advantages over conventional materials, including enhanced water permeability, salt rejection, and durability. This comprehensive review begins by providing an overview of the global water crisis and its implications for human society and the environment. It underscores the urgency of developing sustainable desalination technologies to bridge the widening gap between water supply and demand. The review then delves into the fundamental principles of desalination, emphasizing the central role of membranes in the process. The article proceeds to elucidate the unique structural and chemical properties of graphene that render it a superior membrane material. It discusses the methods of graphene synthesis and fabrication, highlighting key advances in scalable production techniques. Moreover, the review evaluates the performance of graphene-based membranes in various desalination processes, including reverse osmosis and forward osmosis, offering insights into their effectiveness in reducing energy consumption and improving desalination efficiency. One of the major challenges in graphene membrane research lies in maintaining structural integrity and stability under real-world conditions. The review addresses this concern by exploring strategies to enhance membrane robustness, such as functionalization, composite materials, and nanopore engineering. These innovations not only bolster the mechanical properties of graphene membranes but also expand their applicability to diverse desalination scenarios. In addition to performance and durability, cost-effectiveness is a critical factor in the practical implementation of desalination technologies. This article examines the economic aspects of graphene-based membranes, considering production costs, scalability, and the potential for widespread adoption in both industrial and decentralized settings. The review also underscores the importance of addressing environmental and sustainability considerations in membrane technology development. It explores the eco-friendly aspects of graphene-based membranes, including their reduced energy requirements and potential for brine management. Moreover, it highlights the role of graphene in catalysis for the treatment of concentrated brine streams, reducing environmental impact. Furthermore, this review provides a glimpse into ongoing research and future directions in graphene membrane technology. It discusses emerging trends, such as 2D materials beyond graphene and advanced characterization techniques, which promise to further enhance the performance and applicability of graphene-based membranes in water desalination. "The Promise of Graphene: Advancing Water Desalination with Innovative Membranes" offers a comprehensive overview of the exciting developments in graphene membrane research and their potential to revolutionize water desalination. With its unique combination of properties, graphene holds the key to addressing the global freshwater scarcity crisis, paving the way for a more sustainable and water-secure future.

Keywords: *Graphene, Membranes, Water Desalination, Salt Rejection, Nanopores, Sustainability, Reverse Osmosis, Forward Osmosis, Freshwater Production.*

Introduction

Water scarcity is an increasingly pressing global challenge that threatens the well-being of both human populations and the environment. As the world's population continues to grow, urbanize, and industrialize, the demand for freshwater has surged, while the supply of naturally available freshwater remains relatively constant. This growing gap between supply and demand for freshwater resources has led to widespread water scarcity in various regions, exacerbating social, economic, and environmental problems.[1] Access to clean and safe drinking water is a fundamental human right, and addressing water scarcity is essential for sustainable development. Desalination of water, particularly through innovative graphene-based membranes, holds the promise of alleviating this crisis and providing a reliable source of freshwater to meet the growing needs of our society. One of the primary drivers of water scarcity is the unequal distribution of freshwater resources around the world. While some regions are blessed with abundant freshwater, others suffer from chronic water shortages. This geographical imbalance in water availability is further aggravated by factors such as climate change, pollution, and over-extraction of groundwater.[2] As a result, millions of people are affected by water scarcity, leading to a range of social and economic challenges. Communities lacking access to clean water often face health risks due to the consumption of contaminated water, hindering progress in education, livelihoods, and overall quality of life. Moreover, water scarcity can fuel conflicts, as competition for limited water resources intensifies among different user groups, industries, and even nations. In this context, the importance of developing sustainable solutions to bridge the gap between water supply and demand cannot be overstated.[3]

Desalination, the process of removing salt and impurities from seawater or brackish water to make it potable or suitable for industrial use, has emerged as a critical technology in addressing the world's growing water scarcity crisis. As global population continues to soar and freshwater resources dwindle due to factors such as climate change, over-extraction, and pollution, the need for sustainable and efficient desalination methods becomes increasingly imperative. In this context, graphene-based membranes have garnered significant attention for their potential to revolutionize the desalination industry.[4] This article explores the pressing desalination imperative, the challenges it presents, and how graphene-based membranes hold promise in providing a sustainable solution to meet the ever-increasing demand for freshwater. The desalination imperative arises from a confluence of factors that collectively threaten global water security. Firstly, the world's population is expected to reach 9.7 billion by 2050, placing unprecedented stress on existing freshwater sources.[5] Furthermore, climate change has intensified the frequency and severity of droughts, altering precipitation patterns and exacerbating water scarcity in many regions. Traditional sources of freshwater, such as rivers and underground aquifers, are depleting rapidly due to over-extraction for agriculture, industry, and urbanization. Pollution, both chemical and microbial, further diminishes the quality of available water resources. As a result, millions of people around the world face water shortages, and the problem is projected to worsen unless innovative solutions are employed.[6]



Graphical Abstract: Graphene/Graphene Oxide Based Membrane for Water Desalination

Desalination technologies have emerged as a key strategy to bridge the widening gap between freshwater supply and demand. However, they are not without their challenges. Conventional desalination methods, such as reverse osmosis and distillation, are energy-intensive, environmentally taxing, and economically burdensome.[4] The disposal of brine, a byproduct of desalination, poses ecological risks to marine ecosystems when not managed properly. Thus, there is an urgent need for more sustainable and efficient desalination techniques. This is where graphene-based membranes come into play. Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits remarkable properties such as exceptional mechanical strength, thermal conductivity, and, critically, impermeability to all gases and liquids except water. These properties make graphene an ideal candidate for membrane-based desalination processes that could significantly reduce energy consumption, environmental impact, and costs associated with desalination.[7] The desalination imperative is an urgent call to address the growing global water crisis resulting from population growth, climate change, over-extraction, and pollution. Traditional desalination methods have limitations in terms of energy consumption, environmental impact, and economic feasibility. The promise of graphene-based membranes in advancing water desalination offers a ray of hope in meeting the burgeoning demand for freshwater while mitigating the negative consequences of conventional desalination processes.[8]This article will delve deeper into the innovative aspects of graphene-based membranes and their potential to transform the desalination landscape, providing a sustainable solution to ensure water security in the face of a changing world.

Currently, the two most widely used desalination methods are reverse osmosis (RO) and distillation, each with its own advantages and limitations. Reverse osmosis, a dominant technology in desalination, relies on semipermeable membranes to separate salt and other impurities from water under pressure.[9] These membranes have evolved over the years, becoming more efficient and durable, allowing for higher salt removal rates and lower energy consumption. However, the existing RO membranes have their drawbacks, such as fouling and scaling issues, which require frequent maintenance and cleaning, increasing operational costs. Moreover, RO systems are energy-intensive, primarily due to the high-pressure pumps required to force water through the membranes. This energy demand has prompted the search for alternative materials and technologies to improve the efficiency and sustainability of desalination processes.[10] Distillation, on the other hand, involves the heating of saline water to create vapor, which is then condensed into fresh water. While distillation has been used for centuries and is energy-efficient in regions with abundant heat sources, it still requires substantial energy input, making it less feasible in many areas. Furthermore, both RO and distillation methods generate brine as a byproduct, which must be managed carefully to avoid environmental harm. This poses an additional challenge for large-scale desalination plants, especially in regions where proper brine disposal is problematic.[11] To overcome these challenges and take desalination to the next level, researchers have turned their attention to graphene-based membranes as a promising avenue for innovation. The current state of desalination is marked by a reliance on established technologies like reverse osmosis and distillation, which have made significant strides in efficiency and effectiveness.However, these methods still face challenges related to energy consumption, maintenance, and brine disposal. In the pursuit of more sustainable and efficient desalination processes, the integration of graphene-based membranes represents an exciting frontier. The exceptional properties of graphene, such as its high mechanical strength, exceptional thermal conductivity, and atomically thin structure, hold great promise for addressing the existing limitations of desalination technologies.[12-14] In the following sections of this review article, we will delve deeper into the potential of graphene-based membranes and how they may revolutionize the field of water desalination.

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has garnered immense attention and fascination in the field of materials science and engineering since its isolation in 2004 by Andre Geim and Konstantin Novoselov, earning them the Nobel Prize in Physics in 2010. This two-dimensional material possesses a plethora of extraordinary properties that make it truly exceptional. Its remarkable electrical conductivity, mechanical strength, thermal conductivity, and unparalleled surface area have led to a wide array of applications across various industries, including electronics, energy storage, and even medical devices. One area where graphene has shown immense promise is in the field of water desalination, where its unique characteristics open up new avenues for addressing one of the most pressing global challenges: access to clean and potable water.[15-17] Graphene's exceptional promise begins with its outstanding mechanical properties. It is renowned for its extraordinary tensile strength, exceeding that of steel, making it incredibly robust and durable. This resilience is a crucial attribute in the context of water desalination, where membranes must withstand high pressures, temperature fluctuations, and aggressive chemicals. Additionally, graphene is incredibly thin, with a thickness of just one atom.This property is particularly advantageous in membrane applications, as it allows for the creation of ultrathin, yet effective barriers for separating salts and impurities from water. The nanoscale thickness of graphene membranes results in significantly reduced energy consumption compared to traditional desalination methods, as water molecules can pass through the membrane with much less resistance. Consequently, the energy efficiency of desalination processes can be dramatically improved, which is paramount in regions suffering from water scarcity and energy constraints.[18]

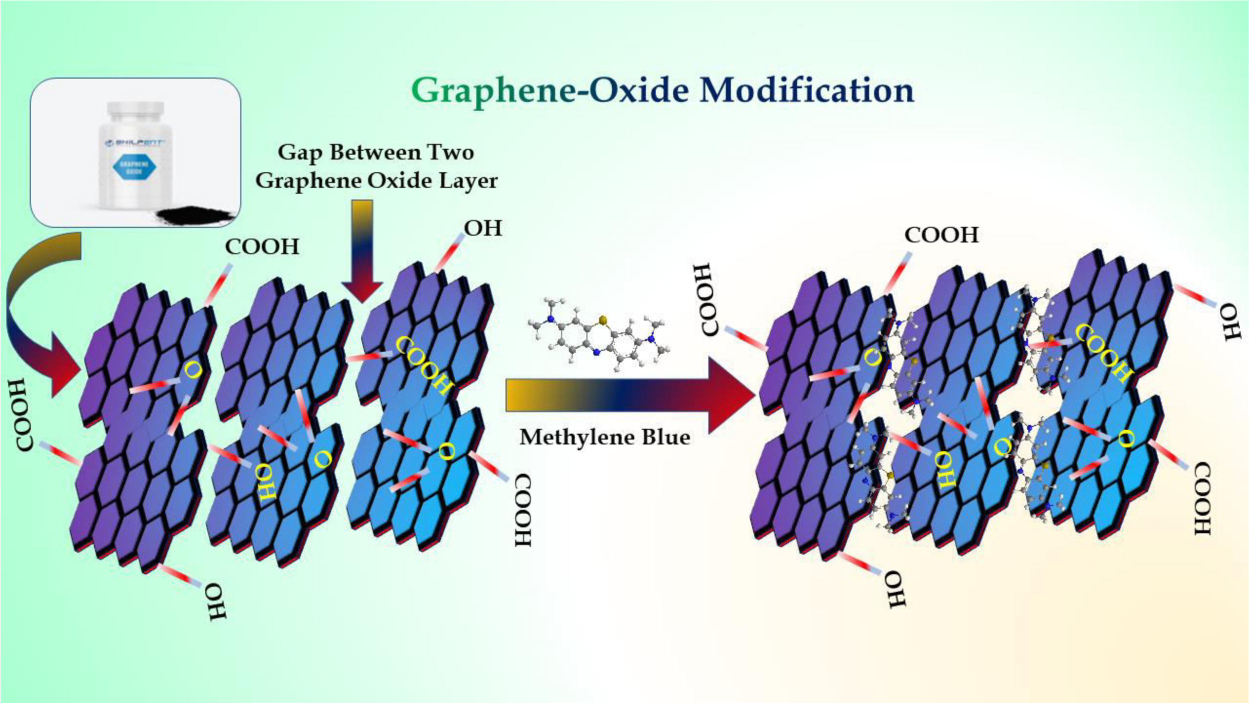


Figure 1: Modification of Graphene Oxide

Graphene's exceptional electrical and thermal conductivity further enhances its suitability for desalination applications. The high electrical conductivity of graphene allows for the development of advanced electrochemical desalination techniques, such as capacitive deionization, which relies on the movement of ions under the influence of an electrical field. Graphene-based electrodes in capacitive deionization systems have demonstrated remarkable ion removal capacities, making them highly effective for desalination purposes. Furthermore, graphene's exceptional thermal conductivity enables efficient thermal desalination processes, such as multi-effect distillation, where heat is utilized to vaporize water, leaving behind salts and impurities.[19] The ability of graphene-based materials to efficiently transfer and dissipate heat can significantly enhance the performance of such thermal desalination systems, contributing to their overall sustainability and effectiveness. Graphene's surface area, another key attribute, is pivotal in enhancing desalination efficiency. The theoretical specific surface area of graphene is approximately 2,630 square meters per gram, providing an immense platform for interactions between water molecules and the graphene surface. This large surface area allows for a higher density of functional groups or pores, which can be tailored to selectively adsorb or reject specific ions and contaminants.[7]The tunability of graphene's surface properties makes it possible to design membranes with precise selectivity for different salt ions, allowing for the creation of customized desalination solutions. Moreover, the hydrophobic nature of graphene ensures minimal fouling and biofouling, further extending the lifespan and performance of graphene-based desalination membranes.[20] Graphene's exceptional promise as a material is undeniable, and its potential to revolutionize the field of water desalination is a testament to its unique properties. Its outstanding mechanical strength, nanoscale thickness, electrical and thermal conductivity, and immense surface area all contribute to its suitability for desalination applications. By harnessing these attributes, researchers are actively exploring innovative graphene-based membrane technologies that hold the promise of significantly improving the efficiency, sustainability, and accessibility of freshwater production, ultimately addressing the critical global challenge of providing clean and potable water to populations in need.As ongoing research continues to unveil new possibilities and overcome existing challenges, the integration of graphene-based membranes into practical desalination systems appears increasingly within reach, offering hope for a more water-secure future.[21, 22]

Traditional desalination methods, such as distillation and reverse osmosis, have been widely used for decades to produce freshwater from saline sources. However, these methods come with several drawbacks. Distillation requires a significant amount of energy to heat seawater and collect freshwater vapor. Reverse osmosis, while more energy-efficient, still demands substantial power for the high-pressure pumps used to force water through a semi-permeable membrane. The energy consumption associated with conventional desalination processes contributes to greenhouse gas emissions and environmental degradation. It is essential to seek more sustainable alternatives. Fouling, a process where impurities and microorganisms accumulate on the membrane surface, is a persistent problem in reverse osmosis membranes. It necessitates regular maintenance and replacement, adding to operational costs. Graphene-based membranes offer a promising alternative to traditional desalination techniques, addressing many of the challenges mentioned above.[23, 24] Graphene's single-layer structure allows it to act as an ideal molecular sieve. Its pores are so small that only water molecules can pass through while excluding salts and other impurities. This intrinsic property makes graphene-based membranes highly efficient in salt rejection. Graphene-based desalination membranes require significantly less energy compared to traditional methods. The exceptional permeability of graphene allows water to flow through the membrane with minimal resistance, reducing the need for high-pressure pumps in reverse osmosis. Lower energy consumption translates into a reduced carbon footprint. By harnessing the properties of graphene, desalination processes can become more environmentally friendly and sustainable.[25]Graphene's smooth surface and chemical properties make it resistant to fouling. Its impermeability to most substances prevents the accumulation of impurities on the membrane, leading to longer operational lifespans and reduced maintenance costs. Graphene-based membranes can be fabricated using various methods, including chemical vapor deposition and liquid-phase exfoliation. As researchers continue to refine production techniques, the scalability of graphene-based desalination membranes improves, potentially leading to cost-effective large-scale implementation. Graphene-based membranes for water desalination are still in the research and development stage, but significant progress has been made. Researchers have successfully demonstrated the feasibility of these membranes in laboratory settings and small-scale pilot projects.[26]

Scientists have created nanoporous graphene membranes by introducing controlled defects into the graphene lattice. These defects serve as size-selective pores, allowing water molecules to pass through while blocking larger salt ions. This approach has shown promising results in terms of salt rejection and water permeability. Graphene oxide, a derivative of graphene, has been used to fabricate desalination membranes. These membranes exhibit good salt rejection properties and can be functionalized to enhance their performance further. Composite membranes combining graphene with other materials, such as polymers or nanoparticles, have been developed. These hybrid membranes aim to capitalize on graphene's unique properties while addressing some of its limitations, such as mechanical strength. Several startups and companies have entered the field of graphene-based water desalination membranes. They are actively working on scaling up production and commercializing this technology.[27, 28]

While graphene-based membranes hold great promise for water desalination, several challenges must be addressed to realize their full potential: The production cost of high-quality graphene remains a significant hurdle. Developing cost-effective manufacturing methods is crucial for the widespread adoption of graphene-based desalination membranes. Scaling up production while maintaining membrane quality and performance is a complex task.Researchers and companies are actively exploring scalable manufacturing techniques. Ensuring the long-term durability of graphene-based membranes in real-world desalination plants is essential. This includes addressing issues related to fouling, chemical stability, and mechanical robustness. While graphene-based membranes have the potential to reduce the environmental impact of desalination, the environmental consequences of large-scale graphene production must also be considered and minimized.[29]The development of graphene-based membranes for water desalination represents a groundbreaking innovation with the potential to address the growing global water scarcity crisis. These membranes offer remarkable salt rejection properties, low energy requirements, and resistance to fouling, making them a promising alternative to traditional desalination methods. While challenges such as cost reduction, scalability, and long-term durability must be overcome, ongoing research and commercial ventures are driving progress in this field. With continued advancements, graphene-based membranes could revolutionize the desalination industry, providing a sustainable and environmentally friendly solution to ensure access to clean and freshwater resources for generations to come.[30]

Water scarcity is a critical global challenge that demands urgent attention and innovative solutions. The unequal distribution of freshwater resources and the environmental consequences of traditional desalination methods underscore the importance of exploring new technologies to address this issue. Graphene-based membranes hold tremendous promise in advancing water desalination by making the process more efficient, cost-effective, and environmentally friendly. As research and development efforts continue to progress in this field, it is hopeful that graphene-based membranes and other innovative solutions will help bridge the gap between water supply and demand, ensuring a sustainable and secure freshwater future for generations to come.[31]

Preparation of Graphene Based-Membrane.

Membrane separation technology emerges as a momentous scheme in water desalination, owing to its dominance in energy-saving, high efficiency, ecological benefits, and recyclability. A total of eight various, utterly endorsed methodologies have been appraised in this review, which fabricates Graphene Oxide (GO) derivative membranes. Among these eight, five methodologies are considered small-scale techniques: vacuum filtration, pressure-assisted assembly, spin coating, dip coating, and drop casting. The other three methodologies—bar or doctor blade coating, slot-die coating, and spray coating—are addressed as large-scale techniques.[32]

Small Scale Techniques

Vacuum Filtration: One of the most straightforward and common methods to fabricate GO-based membranes is the vacuum filtration method. Vacuum filtration is a procedure that increases the filtration rate by removing air from under the filter paper. In suction filtration, a pressure gradient provides a force on the solution, aiding the liquid in passing through. A suction pump is used to remove air from the Buchner flask. First, GO is manufactured, and a homogeneous dispersion of GO in water is created using ultrasound. Then, under vacuum, the diluted GO dispersion is filtered through a porous substrate, creating a pressure differential across the filter medium. The pressure gradient draws the solvent into the porous substrate. This method involves a significant removal of solvent and takes a considerable amount of time. The GO membrane is deposited on a matrix membrane with a rigid thickness. However, by varying the concentration or volume of the GO precursor solution, the thickness of GO-based membranes can be adjusted. Yong et al. examined the deposition of GO flakes with a 10 nm thickness on porous alumina or nylon filters. Hung et al. explored the agglomeration of r GO flakes with thicknesses ranging from 18 to 25 nm on porous alumina or nylon filters using the filtration method. Both were used for organic solvent nanofiltration. The organic solvent permeance was notably high for the latter filtration membrane due to the increased interlayer distance resulting from solvation, reaching up to 80 LMH per bar. Jin and his co-workers investigated a GO ceramic composite membrane with a 95.2% rejection rate for dimethyl carbonate under vacuum filtration. Xu et al. proposed a $TiO2$-doped GO nanomembrane with a 3.5 nm pore size, which exhibited selectivity for RB and MO of up to 100%. Cheng et al. investigated a GO or polyacrylamide membrane with a 0.68 nm interlayer distance, which can achieve selectivity of up to 95.43%.[33]

This elementary functioning of vacuum filtration furnishes a GO-based membrane of uniform thickness, and this certain approach prevails at an elevated rate of GO utilization. But small and endangered membrane area are flaws of this method. Pressure-assisted filtration method: This approach includes a filtration process where positive pressure has been prospected with the diffusion of GO for precipitating GO flakes onto the matrix membrane. Exceedingly methodized orientation of pressure-aided GO membrane is perceptible from Transmission electron microscopy (TEM). Like pressure-assisted GO membrane, vacuum filtration method procures a sloppy structure with less ordered orientation at the top. Also, a high dismissal rate and flux are prevailed by a highly aligned pressure-assisted membrane. Yuan et al. probed COOH functionalized GO flakes utilizing a pressure-assisted assembly method. Nie et al. fabricated deposition of GO onto porous nylon for fabricating an organic solvent nanofiltration membrane employing this method. Pressure-assisted assembly method proffers a well-organized, highly loaded, and well-stocked dense morphology, and furthermore, an upswing in the refusal rate for sludges has been perceived than the vacuum filtration method, having an unbound structure with less organized layers. Because of owning a lamellar morphology, a highly ordered pressure-assisted GO membrane transpires as an encouraging solution ascribe to its highly scalability, efficacious separation proficiency, and water permeability. Accordingly, well-stacked GO membrane can be exercised for NF & RO in seawater desalination method. After amidating carboxyl groups of GO with amines in polyethylene imine (PEI), Lu et al. implanted PEI onto GO nanosheet and probed PGOM-600 and PGO 1000 composite membrane using the vapor filtration method for synthetic organic dye eviction.[12, 26, 34]

***Spin Coating Method**:* Spin coating includes the fabrication of the homogeneous fine film on the flat surface of the substrates by coating a solution of material which is worthwhile in an "ink" (solvent). In four steps, this process is dispatched - deposition, spin-up, spin-off, and evaporation. The commencing stage is deposition. The solution is deposited on the substrate, which is accommodated on the rotating disc. Regarding static spin coating, the substrate withstands spinning after assigning the solution to be covered onto the substrate. In that instance, dynamic spin coating, the substrate is gyrating. The second step is to spin up; the expedient spinning speed is achieved by the substrate. Nevertheless, different revolving rates of the fluid and substrate at the beginnings, but they concur later. The dispersal of the smeared solution on the surface of the substrate occurs due to its centrifugal force. In the step of spin-off, the color of the film changes because it is flung off, and the film dries, which can be observed through color alteration. At the ending stage, the solvent volatilizes homogeneously, and expeditious revolution leads to the vaporization of highly volatile components, which is responsible for narrowing the exerted layer. This method is customary in membrane formation, where a GO dispersion is applied using a spin coater. The convenience of this method lies in the fabrication of a well-oriented, uniform, and exclusive GO membrane. The thickness of the membrane can be adjusted by the viscosity of the GO dispersion and the spinning rate. Kin et al. investigated a 3-10nm thick, well-aligned, spin-coated few layers of graphene membrane for separating hydrogen or carbon dioxide. Chie et al. demonstrated a spin-coated GO membrane with a 20nm thickness by spin-coating GO flakes on porous alumina.[14, 35, 36]

***Dip Coating*:**It is an affordable, effortless, and effectual procedure to invent a thin film. The substrate is first submerged into the solution containing coating material. The substrate is plunged into the solution at a restrained rate for an abundant time to confirm the adequate interaction between the substrate and the solution, and the time is called the Dwell time. Deposition and drainage: When the substrate is extracted from the dunked condition upward at a uniform speed, a thin covering is settled on the substrate, and the surface sees the evacuation of redundant liquid take place. Evaporation: The solvent on the varnished film onto the surface of the substrate is vaporized by heating. To fabricate a GO membrane, the method requires lowering the lustrous substrate into a stock GO dispersion to dip. As the substrate is pulled out, a thin film of GO layer dries, which is accountable for plating abandon onto the surface of the substrate, and ultimately, a GO membrane is secured. The higher the dragging speed, the broader the coating perches on the surface. The benefit is the thickness of the membrane can be restrained by moderating GO concentration, temperature of the substrate, and speed of pulling. Zhang et al. probed dip-coated hollow fiber Rebase membrane to magnify the accuracy of nitrogen or carbon dioxide. Lou et al. composed to refine the hydrophilicity of the membrane by silane modification. Goh et al. utilized the dip-coating method to construct a polyamide-imide hollow fiber membrane. Eum et al. fabricated a polyvinylidene fluoride hollow fiber membrane with ethylene diamine functionalization. Drop-casting method: This introductory approach includes small coatings on small molecules with a smooth surface. The simple film shaping technique includes lodging the desired material, i.e., GO dispersion on the substrate, followed by vaporizing the solvent. The primacy is the dissipation of less material. It is formidable to acquire a uniform GO membrane, which is answerable for the deficit of surface ordering form. Sum et al. exerted this procedure for ion sieving prosecution. Church et al. invented a self-standing GO membrane to block the motion of ethanol throughout a pervaporation experiment.[21, 37, 38]

Spray Coating: GO dispersion into nanoscopic droplets is achieved by utilizing a spray gun, which is then dispensed onto desired surfaces on the prepared substrate uniformly. The solvent, after evaporating from the substrates, results in a GO layer. This method constructs a membrane on a mass scale, which is responsible for shaping a GO membrane with a large area. However, the lack of uniformity in the GO membrane is the main drawback of this method. Ibrahim et al. fabricated a membrane using this method for gas separation.[36]

Slot Die Coating: It is a versatile and highly scalable technique for the rapid deposition of a homogeneous wet film on a substrate. This technique is cost-effective and offers high uniformity across a large area, both in terms of length and width. The fundamental advantage is that this process provides adjustable thickness ranging from 10 nm to hundreds of nm. The desired coating material, liquefied into a slurry, is applied to the substrate through a precision slot die head.[39]

Doctor Blade Coating: This technique is a widely employed method to produce a significant amount of GO membrane. Akkari et al. designed and synthesized a GO membrane using this technique to overlay a nylon substrate. Choi et al. fabricated a GONR gel for membrane production using the doctor blade method. The main challenges of this method are related to the shape of the substrate, slow evaporation under natural drying conditions, and the difficulty of fabricating a GO membrane on a 10 nm scale.[40, 41]

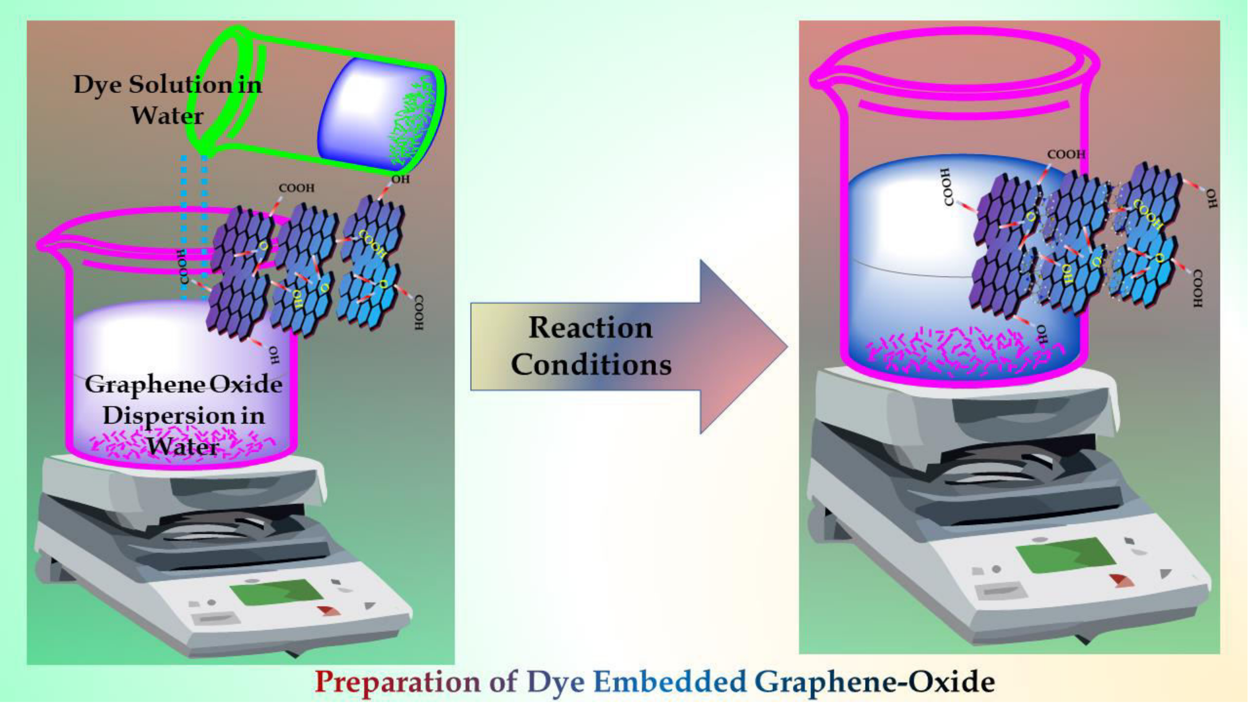


Figure 2: Graphene-Oxide Modification using Dye Embedding

Separation of Ionic Solutes by GO nanofiltration Membrane

Size Exclusion: This is a particle elimination process that impedes the transit of ionic and larger molecules through pores smaller in size than the particles. The separation of ionic species in the size exclusion mechanism is based on size. By fine-tuning the deployment of GO nanochannels, it becomes attainable to create a membrane for nanofiltration with a wispy interlayer spacing by interpolating definite-sized nanofillers for water purification.[42, 43]

Donnan Exclusion: According to Emamjomeh et al., the separation mechanism in nanofiltration (NF) mainly encompasses the size of molecules and electrical interactions between the surface of the membrane and ionic solutes. The Donnan exclusion method draws in electrostatic interactions between fixed charges on the surface of the membrane and ions. When the charge of the membrane matrix is negative, it excludes negatively charged ionic solutes through repulsion and permits positively charged ionic solutes to pass through. Due to the deprotonation of carboxyl groups on the GO nanosheets, negative charges occur on the GO. A negatively charged GO membrane efficiently rejects all negatively charged organic molecules or ionic solutes. A positively charged GO nanosheet framework is constructed by incorporating amine-abundant molecules like polyamidoamine dendrimers and HPEI. The positively charged membrane with 95% efficacy shows heavy metal rejection. Adsorption: Transition metals hydrate cations due to interactions with GO, adsorb onto various regions of GO nanosheets and are accordingly occluded by the GO membrane, resulting in outstanding selectivity of GO sheets.[44, 45]

Advantages of Graphene-based Membranes over Traditional Membranes

Membrane technologies have acquired acclaim because of their affordability, facile servicing, and high rejection rate. Headway in flourishing and expanding nanotechnologies, devising new nanomaterials like graphene, GO, CNTs for restoring presently used composites is occurring significantly. Graphene has the utmost supremacy due to its highwater permeability. Graphene, a 2D material produced from natural graphite, is made up of sp^2 hybridized carbon atoms organized in a honeycomb structure. The atomic thickness of graphene indemnifies its high fluid permeability and selectivity. The graphene membrane holds an ultrasmall pore size, which is accountable for size-selective transportation through the nanopores between adjoining stacked graphene sheets. The interspace between adjacent graphene sheets is 0.3-0.7 nm to formulate effortless water flow and a high non-acceptance rate of tainting ions. Modulating interlayer spacing between adjoining stacked graphene sheets and pore size selectivity has been executed. In consequence, permeability and selectivity are two prime benefits of graphene-based nanomembranes over traditional ones. In several forms, graphene is employed as the chief constructing material of desalination membranes, such as pristine graphene, GO, and rGO.It is far-reaching to fabricate nanoporous graphene layers to utilize as water desalination membranes. Flaws are consciously made in graphene by plasma, laser beam perforation, selective oxidation, electron beam, ion etching, and ion bombardment. An adequate curiosity has come to light in utilizing G and GO to fabricate filter membranes, as nanoporous graphene (NPG) has appreciably higher permeability than accessible RO membrane materials. But the effectuality of desalination has diminished by reason of the porosity of NPGs. At present, researchers have been involved in inventing new graphene-based materials, which are marked as arising and propitious candidate materials for their substantial strength, cohesion, and flexibility.[46-48]

Fouling control is one of the most indispensable accomplishments of a graphene-based membrane. Graphene shows phenomenal resistance to chlorine, which engenders a curb to biofouling. Biofouling resistance, thinness, hydrophilicity, and ultra-small pore size are the most instinctual benefits of a graphene-based membrane, conserving high permeability and selectivity, making it an auspicious material for future generation seawater desalination systems. More extensive investigation and furtherance in fabrication and maturing of a new synthetic route emerge as crucial commitments to unfasten the thorough benefits of graphene and make it the most optimistic of those novel materials.One of the universally traversed graphene-based materials, GO, produced by the oxidation of graphite (Gr), embraces one atomic layer with oxidized functional groups on the edge of the GO sheets. Owing to the hydrophilic nature of GO and realizable moderation of GO sheets, copious graphene-based materials have been unfolded recently to ameliorate durability, elasticity, and conductivity. Thus, graphene is operated to be in the service of as a prime material for emerging foremost membranes.[34, 49, 50]

Graphene-based Desalination

Graphene-based desalination represents a cutting-edge approach to tackling one of the most pressing global challenges: the scarcity of fresh water. Graphene, a one-atom-thick sheet of carbon atoms arranged in a hexagonal lattice, has demonstrated remarkable properties that make it an ideal candidate for desalination processes. Its exceptional electrical conductivity, high mechanical strength, and, most importantly, its remarkable permeability to water molecules, enable it to effectively filter out salt and impurities from seawater, turning it into freshwater. This breakthrough technology holds the promise of making desalination more energy-efficient and cost-effective, ultimately addressing water shortages in arid regions and easing the strain on the world's water resources. As research and development in this field continue, graphene-based desalination has the potential to revolutionize the way we provide clean and accessible drinking water to the ever-growing global population.[51]

Monolayer Nano porous Graphene Desalination Membrane

Selectivity and Permeability—This is a graphene membrane with a single-atomic width and sub-nanometer pores, serving as an RO membrane. Nano-porous graphene is endowed with a marvelous rate of water flow, up to 66.1 cm^{-2} day^{-1} MPa^{-1}, and a salt rejection rate greater than 99%. Thomas et al. projected six salt rejection mechanisms by a monolayer graphene desalination membrane: size exclusion, charge repulsion, interaction between the chemical structure inside nanopores and solute ions, entropic differences instigated by graphene, and subtler effects incorporating specified interactions with pores, evaluated in biological membranes in place of the graphene membrane. Through sub-nanometer-sized pores, water penetrates with ease, but salt ions get impeded due to their larger size compared to water molecules. The atomic thickness of graphene is responsible for graphene's ultrahigh water penetrability, leading to a noteworthy inexpensiveness of desalination plants and capital expenditure. Achieving selectivity while sustaining a high rate of water permeability is the key ambition of fabricating graphene membranes.[52]

Challenges and Solutions—Numerous applicable exploratory studies have brought about the evolution of ample production of defect-free single-layer graphene membranes of large areas with controlled, uniformly-sized, high-density nanopores, which can be enormously demanding. During the development and graphene transfer process, both inherent and extraneous defects have interfered, bringing down the selectivity of the membrane for water desalination, particularly for smaller molecules like salts.[53]

With respect to the challenges of CVD graphene, especially when it is grown on the surfaces of metallic crystal materials, particularly on copper foil, it has been revealed as the most practical growth substrate for emerging monolayer CVD graphene. CVD graphene transfer is one of the essential steps in its implementation. However, the advancement in the scalability of large-area CVD graphene transfer has been hampered due to complications such as high business expenses, achieving impurity-free CVD graphene, scalable manufacturing, and the utilization of abrasive chemicals.Currently, Roll-to-Roll CVD graphene transfer has emerged as the primary goal, with synthesized graphene taking the form of a roll-type substrate arranged appropriately inside a tubular furnace, promoting mass-scale fabrication and uniformity of graphene films.[54] This system allows for general graphene to be overlaid and preserved with fine polymer films of various ranges on a graphene-on-catalyst substrate roll, leading to an efficient transfer to roll-to-roll CVD graphene. This is a cost and time-effective method because of its economic scalability. According to Bav et al. the continuous mass-scale processing of graphene-based devices is achievable due to the scalability and operability of CVD graphene. To improve adaptability, it was necessary to undertake the fabrication of a larger-sized membrane of a few microns, as suggested by O'Hern (2012).[55] A monolayer CVD graphene was used to construct a graphene composite membrane employing a TEM grid as mechanical support and oxygen plasma therapy for fabricating nanopores. It was found that widespread implementation and efficacy of the graphene membrane with tractable sub-nanopores' size resulted in increased water penetrability and membrane active area, which was due to the reduction of cracks and defects. However, salt selectivity, as well as the rejection rate, was small due to the unplanned size and disorganized location of intrinsic pores. As a result, managing uniformly sized high-density nanopores is a challenging task. Surwade et al. proposed a monolayer graphene membrane at barometric pressure through CVD on a copper foil catalyst. The embodiment of nanopores through the oxygen etching process enhances selectivity at low porosity but decreases at high porosity. Recently, nanopores with controlled sizes have been devised by ion-electron bombardment, as suggested by Russo et al., Koenig et al., Cheng et al., and Wu et al. Additionally, the oxidative process proposed by Koenig et al., Cheng et al., and Wu et al. also appears as an instrument to fabricate graphene nanopores with a larger area.[56-58]

In recent times, designing a firmly distributed pore size by irradiating flawed graphene with an electron beam at the carbon knockout potential is a more structured process than oxidative one. This approach builds nanopores to establish a limited membrane area, owing to irradiation with a high-voltage electron beam that intensifies blemishes in the pore. O'Hern et al. recommend graphene nanomembranes with controlled high-density nanopores by gallium ion shelling for selective ion transformation using this procedure. During the manufacture of centimeter-scale single-layer graphene, various intrinsic and extrinsic deficiencies throughout growth and the graphene transfer process in the range of 100 nm are accountable for constraints in the real-world implementation of monolayer graphene membranes.[59]

O'Hern et al. (2015) suggested and demonstrated the sealing process to retard the unruly extension and transfer of flaws, making the remaining monolayer graphene usable for nanofiltration of salts. It displayed a dismissal rate of 70% for $MgSO_4$, 83% for dextran, and 90% for allura red, but it showed a negative refusal rate for NaCl, i.e., NaCl penetrated through leakage. Hence, the sealing method did not prove fortunate in achieving salt rejection. Recently, an interfacial polymerization method has been realized and embraced to seal macroscopic flaws for sub-nanometer-scale separation by embedding nylon 6,6 within defects, and the fabrication of small pores was achieved through mild UV/ozone oxidation.[60]

Multilayer Graphene Desalination Membrane

The major stumbling block of the classical water purification method is the acidity of refined water and high energy expenditure. Classical RO membranes also suffer from low mechanical power and are not economically friendly due to high operational energy and low thermal resistance. Subsequently, focusing on the fabrication of nano-porous materials applied in RO, various explorations and inspections have come about. Single-layer nano-porous graphene has shown promise and has garnered considerable interest from researchers and scientists as an RO desalination membrane. However, the slit-free, scalable construction of a monolayer graphene membrane over a substantial area with high water penetrability is exceedingly demanding. The synthesis of a multilayer graphene desalination membrane can be a more cost-effective approach with excessive yield in manufacturing. The multilayer graphene membrane is made up of extremely assembled graphene nanosheets. Reliable interlayer hydrogen bonding is responsible for a firm, free-standing membrane. 2D graphene provides exceptional malleability and solution handleability, as well as chemical and thermal stability. Multilayer NPG membranes were analyzed using molecular dynamic simulations (MDS).[61, 62]

The diverse pore sizes are present in the multilayer membrane across various layers. The multilayer graphene desalination membrane exhibits an elevated water flow rate, with a 2.8Å pore size under 500 MPa pressure. This increase is attributed to the immense slip length and lower friction on the graphene sheet. The non-oxidized nanochannel is surrounded by a hydrophobic region of graphene oxide (GO). The increase in water penetrability is due to the surface's hydrophilicity. Water permeability increases with the applied pressure. Water penetrability rises with the increasing applied pressure. On the graphene surface, the appearance of oxygen-accommodating functional groups with hydrogen bond interactions with H_2O eases the flow of water between the hydrophilic oxidized region and the graphene flake. Swelling of the water-logged membrane can occur due to interactions between the hydrophilic region and H_2O, which expedites a decline in dismissal efficiency. Swift water permeation through the graphene nanochannel is possible due to the membrane's porous microstructure. Small ions proceed rapidly due to capillary-driven forces. The multilayer graphene-based membrane has a laminar structure with a characteristic water penetration rate of more than 500 L/m²h/bar under applied pressure for micrometer-thick membranes. According to Hung et al., thicker graphene leads to lower permeability. Bilayer NPG membranes exhibit exceptional salt rejection with an R value of 3 Å. When R is increased to 4.5 Å, bilayer membranes show salt rejection in the range of 85-100%, attributed to significant pore alignment and a larger interlayer spacing; however, rejection efficiency decreases. Therefore, to achieve optimal permeability and rejection rates, both interlayer separation and pore alignment must be adjusted. By adjusting the interlayer separation to 8 Å, substantial pore adjustments result in minimal water flux and consequently a lower rejection rate. Complete pore alignment is advantageous in this scenario, whereas significant interlayer separation leads to a lower rejection rate. Size exclusion, depending on the interlayer spacing between two GO flakes, and electrostatic interactions between charged ions and charged functional groups on the GO surface, are the presiding separation mechanisms. Basic OH- ions interact with the carbonyl and hydroxyl functional groups on the surface of the flakes, and the repulsive force between GO sheets brings about an increase in interlayer spacing. Consequently, there is a brisk permeation of ions such as Na^+, K^+, and OH^- through nanochannels.[63, 64] Transition metal and alkali metal cations can be adsorbed onto GO nanosheets through coordination bonds to an sp3 structure and cation-π interaction with an sp^2 structure, respectively. The size exclusion separation mechanism is based on the interlayer spacing of the graphene oxide (GO) sheets. The existence of oxidized and large percolating regions within the non-oxidized domain of GO sheets accounts for the various interlayer spacings of GO sheets, subsequently affecting the separation efficacy. In the oxidized region, caused by the presence of electrostatic interactions and hydrogen bonding, the mobility of ions and molecules dwindles as they encounter hindrances, resulting in lower interlayer spacing between the pristine and oxidized domains. On the other hand, in the non-oxidized domain, interlayer spacing is more substantial, with the largest spacing observed in the pristine domain. Controlling the interlayer spacing is a critical step, allowing for the adaptation of separation efficacy to address the selectivity of small molecules. However, achieving maximum salt rejection proficiency in this context is a demanding task. Abraham et al. demonstrated a membrane with interlayer spacing ranging from 9.8Å to 6.4Å and achieved success in adjustable ion filtering, reducing swelling, and achieving a 97% rejection rate for NaCl, along with a water permeability of 0.75 $Lm^{-2}h^{-1}$. In a separate study, Lyu, Wen, Kumar, Chen, and Joshi differentiated between graphene oxide foam (GOF) and graphene oxide (GO) membranes. Reduced graphene oxide (rGO) membranes proved more advantageous as desalination membranes due to their smaller pore size and interlayer spacing of 0.35 nm compared to 0.8 nm for GO laminates.[65-67]

GOF with Various Support

A GO membrane can be fabricated using various porous polymer matrix supports. Wang et al. fabricated GO nanosheets on a porous polyacrylonitrile nano fibrous mat (GO PAN) with a 56.7% rejection rate for Na2SO4, and a 10% rejection rate for NaCl, with a water flux of 8 L/m²·h·bar. Hu et al. and Belbe et al. respectively incorporated GO sheets on polydopamine-coated polysulfone supports, crosslinked by 1,3,5-benzenetricarbonyl trichloride, achieving a 58% salt rejection. Yin et al. deposited GO nanosheets on a polyamide (PA) thin film layer, achieving a 94% salt rejection.[68]

Challenge of Water Instability

Salt rejection is not stable under pressure-directed filtration process. The stability of GO is deteriorated in water by hydrated functional groups. On the GO membranes, metal cations in salt solution get adsorbed, which is responsible for less desalination and challenges the feasibility of GO membrane as a desalination membrane in aqueous media. The oxidized region permits H_2O molecules to intercalate between GO sheets, serving as a spacer. As a result, over time, the GO structure disintegrates.[69, 70]

Solution of Water Instability

Chemical crosslinking and π-π interactions between graphene oxide (GO) sheets, achieved through reduction by a strong reductant, enhance stabilization. Zhang et al. proposed a molecular bridge scheme in which a robust GO laminate was fabricated using interlaminar short-chain molecular bridges to resist swelling. This scalable approach stabilizes the GO membrane. Abraham et al. adopted a physical approach to prevent swelling by controlling interlayer spacing through exposing GO membrane stripes to specific humidity levels. Another significant challenge lies in developing a large-area stacked graphene desalination membrane with high mechanical strength and desalination capacity. Otherwise, GO multilayer membranes can be explored as promising and likely candidates for the next generation of water desalination membranes.[71]

Applied Process of Graphene Membrane

Reverse Osmosis

In seawater desalination, pressure-driven reverse osmosis has an indispensable role. Reverse osmosis (RO) is achieved by applying pressure to overcome osmotic pressure, pushing water through a series of filters. Consequently, the purified solvent passes through a semi-permeable membrane, and water molecules are separated from other solutes, which are retained on the pressurized side of the membrane. As a result, RO has made a significant contribution to seawater desalination, particularly in this time of freshwater scarcity, thanks to its cost-effectiveness and environmentally friendly technology. Membrane processes account for nearly 95% of the desalination market (as of 2017), with RO dominating 55% of the membrane process market (as of 2019). However, creating hydrophobic nanochannels between different graphene oxide (GO) layers and hydrophilic gates, thus fine-tuning nanochannel size without introducing morphological flaws to develop a GO-based membrane for RO desalination, remains a work in progress and is not yet available at a large scale. Reverse osmosis has also been employed to combat biofouling, mainly by utilizing GO, which has ion interactions with bacterial cells responsible for its antimicrobial activity, as suggested by Nanda et al. When the ion concentration in the feed water is low, antiscalants like polyacrylic acid (PAA), polymaleic acid (PMA), and polymethacrylic acid (PMMA) are used to absorb on the surface of active crystal extension sites, preventing crystal accumulation. This, in turn, limits their precipitation by suspending ions in the solution through a chelation mechanism, effectively curbing mineral scaling.[72-74]

It is noteworthy for evolving a composite material with twofold anti-scaling and antibiofouling properties. However, in contemporary investigations, it has been depicted that the effectiveness of anti-biofouling properties is elevated, but there is a considerable downturn in anti-scaling properties, especially when there is a substantial concentration of ions in the feedwater. A high surface-to-weight ratio is liable for the moderation of the GO surface. Polyamide RO membranes functionalized with GO gratify both the amplification of the efficacy of anti-biofouling and anti-scaling properties. This is caused by the antiscalant PAA hydrophilic polymer interacting through H-bonding or chemical bonding with hydrophilic groups on GO, which aids in the emergence of a novel composite material with a high level of anti-biofouling and anti-scaling quality. Graphene-based RO desalination has a permeability of 10^{-9} m $Pa^{-1}s^{-1}$, and in some cases, it reaches up to 10-6 m $Pa^{-1}s^{-1}$, and it possesses 99% complete salt rejection characteristics. The hydraulic pressure-directed approach with selectivity, penetrability, anti-scaling, and anti-biofouling properties also assures the criteria of possessing water stability, scalability, economic efficiency, and lower energy requirements. At this time, owing to lower energy imposition, highly penetrable desalination membranes have been enlarged and fabricated, which ameliorates cost depletion by as much as 10%-20% in energy demand. Yi et al. synthesized nitrogen-doped GO quantum dots (N-GOQDs) and chemically transplanted them on the surface of an RO-PA membrane. Fathizadeh et al. probed and synthesized an N-GOQD-modified TFN RO membrane. Rajakumaran et al. embraced a GO-ZnO nanocomposite possessing various morphologies into the PA layer during the interfacial polymerization reaction. Khanzada et al. synthesized a GO-coated TFC RO membrane with lower flux and a slightly higher dismissal rate.[75, 76]

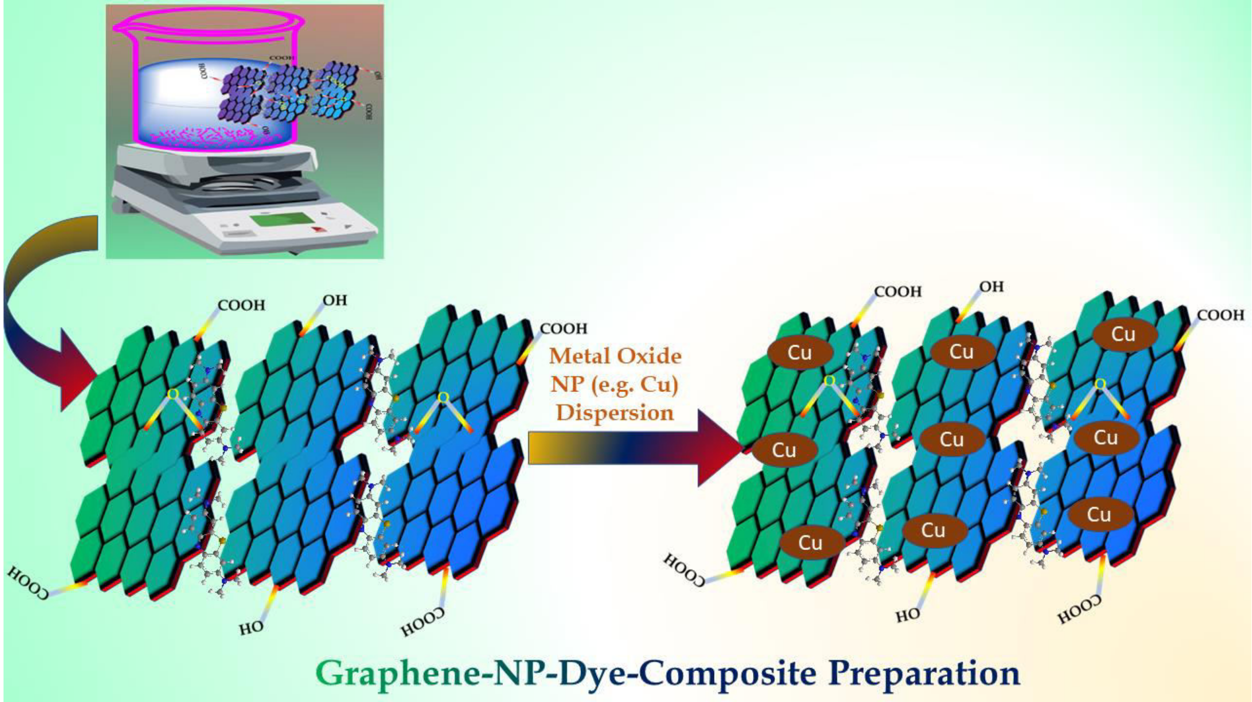


Figure 3: *Preparation of Graphene-Dye-NP Composite*

Forward Osmosis

FO has garnered extensive attention from researchers and scientists. FO, a separation technology, holds more appeal and has been implemented more comprehensively than RO. This is due to the systematic rejection of contaminants, as indicated by She et al. and Kong et al., as well as lower operational energy consumption, as shown by Mazian et al. FO offers high mechanical power and low membrane fouling, as demonstrated by Emadzadeh et al. and Salehi et al., and it also provides high water flux. This hydraulic pressure-driven water treatment innovation is an effective filtration approach operated by osmotic pressure, utilizing a semi-permeable membrane between a low-concentration feed solution and a high-concentration draw solution, which is used to separate water from the dissolved solution.[77]

Graphene emerges as a promising and prospective material for developing FO membranes. The use of GO nanosheets contributes to the enhancement of membrane performance, reducing fouling, improving reverse salt flux, water permeability, and rejection rates. One of the primary challenges in FO membranes is the inadequacy of membranes that effectively address issues during the FO process, such as internal concentration polarization (ICP). While thin film composite (TFC) membranes have been widely used in FO, a significant ICP phenomenon negatively impacts water flux selectivity. Additionally, the polyamide (PA) layer becomes unsuitable for this osmotically driven membrane process due to low water permeability. Another drawback of the PA-TFC membrane is its susceptibility to biological fouling. Therefore, it is essential to mitigate biofouling by using disinfectants containing chlorine, which can induce changes in the polyamide chain.[78, 79]

Researchers place a lot of effort into fabricating and maturing nano materials embraced for FO membranes, such as mixed matrix membranes (MMM) and thin-film nanocomposites (TFN). Zeolite Na and SiO_2 nanoparticles are incorporated into the supported layer. Hydrophilicity, water permeability, and rejection efficacy of the membrane increase for FO due to this incorporation. GO, encompassed in TFC membranes, displays higher water flux, lower structural parameters, and lower specific reverse solute flux (SRSF). Consequently, nanomaterial-incorporated PA layers unveil appreciable performance improvements, such as nano TiO_2 (Niksefat et al.), silica (Liu et al. and Hu et al.), silver (Emadzadeh et al.), hydroxide (Lu et al.) nanoparticles. Among them, GO is the most promising, and its potential for being reformed by various functionalization makes it more distinctive. The GO-PA layer has an elevated surface roughness and surface area, along with high water reflux. Ionita et al. incorporated GO into a PSF (polysulfone) membrane in the support layer. It exhibits increased porosity, lower tortuosity, improved surface hydrophilicity, larger pore size, and enhanced structural properties. Saeedi-Jurkuyeh et al. deposited GO into a TFN-FO membrane during the IP technique to remove heavy metals. Jin et al. probed and synthesized a TFN-based GO-FO membrane to separate Na_2SO_4, $MgCl_2$, and trisodium citrate (TSC) using GO-m-xylylenediamine (GO-MXDA) and TMC solutions.[80-82]

Recent Types of GO Membrane

Freestanding GO membrane, supported GO membrane, and GO-modified composite membrane have matured and evolved through various investigations focusing on the revolution of the GO membrane. Chen et al. synthesized a GO membrane using an evaporation-driven self-assembly method with a tensile strength of 70.7 MPa. Jia et al. probed a cross-linked GO membrane using a vacuum filtration method for ion dialysis separation, which has a K^+/Mg^{2+} selectivity factor of 7.15. Sun et al. fabricated a GO membrane for ion penetration using the drop-casting method to hinder heavy metal salts and organic contaminants (RhB), but it possesses a low rejection rate for sodium salts. Tang et al. manufactured a GO membrane with high water permeability using a pressurized ultrafiltration method for dehydrating 85 wt.% ethanol.[83]

Supported GO Membrane:

Kim et al. fabricated GO/PES with an 8500 Barrer carbon dioxide permeability using the spin-casting method for gas separation. Xu et al. synthesized GO/Al_2O_3 with over 99% ion rejection characteristics through the vacuum filtration method. Feng et al. investigated and improved GOF/AL_2O_3 with a 11.4 kgm-2h-1 water flux and over 99.9% ion rejection efficiency, achieved through the vacuum filtration method for 3.5 wt.% seawater desalination. Hu et al. fabricated GO/PAN with a 2.1-5.8 Lm-2h-1 water flux using the LBL assembly method for water purification.[84]

GO Modified Membrane

Perrault et al. fabricated GO/H-PAN for oil-water separation using the electrospinning method, which exhibits significant antifouling characteristics and a 99% rejection rate. Wang et al. synthesized GO/PESC with a permeability of 7.1 kgm-2MPa^{-1}h^{-1} and a 92.6% rejection efficacy for Mg^{2+} in water treatment. Lai et al. investigated and improved GO/PSF, achieving rejection efficiencies of 95.2% for Na_2SO_4 and 91.1% for Mg_2SO_4 using the phase inversion method.[85]

Conclusion, Commercial Market and Future Perspectives

Graphene-based membranes have emerged as promising tools for advancing water desalination techniques. These innovative membranes, composed of a single layer of carbon atoms arranged in a hexagonal lattice, exhibit extraordinary properties that can significantly enhance the efficiency and sustainability of desalination processes. As a result, they have garnered substantial attention from both researchers and industries. In this review, we delve into the commercial market of graphene-based membranes for water desalination, exploring their current status, challenges, and future prospects. The global water desalination market has been growing steadily due to increasing water scarcity, population growth, and industrial demand for freshwater. Traditional desalination methods, such as reverse osmosis and distillation, have long been the standard. However, they come with high energy consumption, maintenance costs, and environmental concerns. Graphene-based membranes offer a potential solution to these issues. Their exceptional properties, including ultrathin structure, mechanical strength, and high permeability, make them attractive for desalination applications. Graphene oxide and other graphene derivatives have also shown promise due to their tunable nanoporous structure and selective permeation capabilities. Reverse Osmosis Enhancement: Graphene-based membranes have the potential to enhance the efficiency of reverse osmosis (RO) desalination systems. By incorporating graphene into RO membranes, higher water permeability can be achieved while maintaining excellent salt rejection rates. Several companies are exploring the integration of graphene-based materials to improve the performance of RO systems, which could lead to substantial energy savings and reduced operational costs. Nanofiltration: Graphene membranes can be used in nanofiltration processes, allowing for the selective removal of ions and contaminants from brackish water and seawater. This application is gaining traction in the market, as it is more energy-efficient compared to RO and can be used for various industrial purposes, including the treatment of wastewater. Forward Osmosis: Forward osmosis (FO) is an emerging desalination technology that utilizes natural osmotic pressure differences to draw water through a membrane. Graphene-based membranes show promise in FO systems due to their unique properties, which allow for enhanced water transport while maintaining high salt rejection rates. Membrane Distillation: Graphene-based membranes are also being explored for membrane distillation, a thermally driven desalination process. These membranes can offer improved water vapor transport and reduced fouling, potentially leading to more efficient distillation processes.[31, 86, 87]

While the commercial market for graphene-based membranes in water desalination is promising, several challenges must be addressed: Cost: Producing high-quality graphene materials can be expensive. Reducing production costs is crucial to making these membranes economically competitive with existing technologies. Scaling up Production: Scaling up the production of graphene-based membranes to meet the demands of large desalination facilities is a significant challenge. Overcoming this hurdle is essential for widespread adoption. Durability: Graphene-based membranes must exhibit long-term durability and resistance to fouling in real-world desalination applications. Research and development efforts are ongoing to improve their stability and performance. Regulatory Compliance: Meeting regulatory standards and ensuring that graphene-based membranes are safe for use in desalination systems is vital for market acceptance.The commercial market for graphene-based membranes in water desalination holds tremendous promise. As research and development efforts continue, addressing the challenges outlined above will be critical to unlocking the full potential of these membranes. The integration of graphene-based membranes into existing desalination plants and the development of new, more efficient desalination technologies are likely to drive market growth. Graphene-based membranes represent a game-changing innovation in the field of water desalination. Their remarkable properties offer the potential for more sustainable, cost-effective, and energy-efficient desalination processes. While challenges remain, the continued investment and research in this area suggest a bright future for graphene-based membranes in the global water desalination market.[88, 89]

As we reflect on the remarkable strides made in the development and application of graphene-based membranes for water desalination, it becomes abundantly clear that the journey has only just begun. The inherent potential of these revolutionary materials is poised to reshape the landscape of water purification and desalination on a global scale. In this section, we delve into the exciting future prospects and emerging trends that hold promise for graphene-based membranes in this critical field. One of the most significant advantages of graphene-based membranes is their ability to improve the energy efficiency of desalination processes. Researchers are continually exploring ways to fine-tune membrane structures to achieve even higher water permeability while maintaining high salt rejection rates. By addressing the energy-intensive nature of desalination, these membranes have the potential to make this technology more sustainable and cost-effective. The functionalization of graphene membranes with specific groups or materials enables selective filtration, which can target not only salt ions but also specific contaminants and pollutants. This tailored approach opens up possibilities for addressing the growing concerns of water quality and pollution, making graphene-based membranes a versatile solution for a range of water treatment applications beyond desalination. The successful transition of graphene-based membranes from laboratory settings to practical desalination plants is contingent on scalability and cost-effectiveness. Ongoing research and development efforts are focused on optimizing production processes and materials sourcing to make these membranes economically viable for widespread use. The synergy between graphene membranes, nanotechnology, and the Internet of Things (IoT) presents exciting prospects. Integrating graphene-based membranes with IoT sensors can enable real-time monitoring of water quality and membrane performance, providing valuable data for maintenance and process optimization. This combination of technologies has the potential to revolutionize water desalination and treatment. In an era of increasing environmental consciousness, graphene-based membranes offer a solution aligned with sustainable practices. They reduce the reliance on traditional desalination methods, which often involve the use of harmful chemicals and large amounts of energy. The eco-friendly nature of graphene-based membranes aligns with global efforts to conserve resources and reduce environmental impact. The future of water desalination lies in incorporating renewable energy sources such as solar and wind power into the process. Graphene-based membranes can play a pivotal role in these integrated systems, utilizing renewable energy for water purification and desalination. This approach can mitigate the environmental impact of desalination and contribute to a more sustainable water supply. Water scarcity is a global challenge, and the promise of graphene-based membranes in addressing this issue cannot be overstated. These membranes have the potential to bolster water security by providing a reliable source of fresh water in regions where it is desperately needed. In the coming years, we can anticipate the deployment of graphene-based membrane technologies in arid and water-stressed regions to alleviate the water crisis. To unlock the full potential of graphene-based membranes in water desalination, it is imperative that researchers, engineers, and policymakers collaborate across disciplines. Interdisciplinary efforts can drive innovation, facilitate knowledge exchange, and expedite the translation of research findings into practical solutions. The integration of graphene-based membranes in water desalination represents a transformative leap forward in addressing water scarcity and quality issues. The journey ahead promises continued research, innovation, and collaboration, as graphene-based membranes evolve into a cornerstone of sustainable water management and global water security. The future is bright, and the promise of graphene is poised to revolutionize the way we access and purify water, making a profound impact on our world.[90-92]

In the quest for sustainable solutions to the world's growing water scarcity problem, graphene-based membranes have emerged as a beacon of hope. This review has explored the remarkable promise of graphene in advancing water desalination, highlighting the groundbreaking research and developments in this field. As we conclude this comprehensive examination, several key takeaways and future directions become evident. First and foremost, graphene-based membranes have demonstrated their potential to revolutionize water desalination processes. The exceptional permeability, selectivity, and durability of graphene materials have shown tremendous promise in enhancing desalination efficiency. Graphene oxide and its derivatives, as well as pristine graphene, functionalized graphene, and composite materials, have all offered innovative pathways to overcome the limitations of traditional desalination techniques. The advantages of graphene-based membranes extend beyond their filtration capabilities. They are environmentally friendly and energy-efficient, helping to mitigate the environmental impact of desalination processes and reduce operational costs. Moreover, their ability to address fouling issues and withstand high salt concentrations positions them as frontrunners in the desalination landscape. As we look ahead, the commercialization and scalability of graphene-based desalination technologies remain key challenges. The transition from laboratory breakthroughs to real-world applications demands concerted efforts from researchers, policymakers, and industry leaders. Collaboration between academia and the private sector is essential to bridge the gap and bring these innovations to the market. Additionally, we must continue to investigate the long-term performance, safety, and environmental implications of graphene-based membranes. While the initial results are promising, a comprehensive understanding of their behavior under different conditions is crucial to ensure the sustainability and reliability of desalination processes. Furthermore, addressing cost considerations and making graphene-based desalination accessible to regions facing severe water shortages is of paramount importance. Innovations in production methods and material cost reduction will be instrumental in achieving widespread adoption. Graphene-based membranes represent a beacon of hope in the world's water desalination efforts. Their unparalleled properties and potential for sustainable, cost-effective, and environmentally friendly solutions have ignited a wave of excitement within the scientific community.[48, 93, 94] By overcoming the current challenges and advancing research and development efforts, we can harness the full potential of graphene in addressing the global water crisis.The promise of graphene in advancing water desalination is no longer a distant dream but a tangible reality. As we embark on this transformative journey, let our collective commitment and collaboration pave the way for a more water-secure and sustainable future. In the coming years, graphene-based membranes are poised to play a pivotal role in the global quest for fresh water, and the possibilities are truly boundless. This review article aims to provide a comprehensive overview of the promise and challenges of graphene-based membranes in water desalination, shedding light on their commercial potential in addressing the growing global need for freshwater resources.

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