C- Nanomaterials Subordinated Membrane Technology for Obtaining Encirclement of Compassionate Innocuous Potable Water

By

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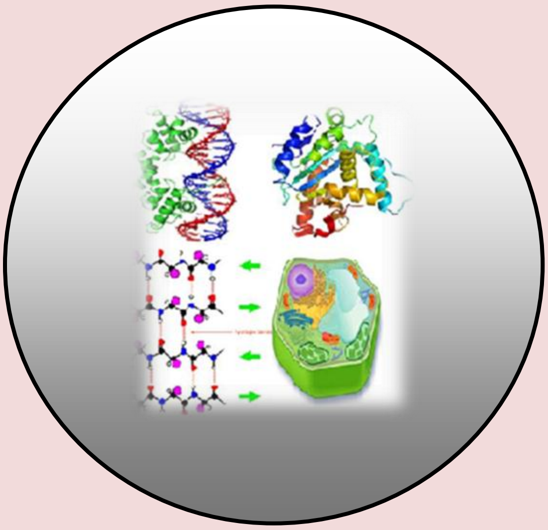

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ABSTRACT

New technologies are required to improve desalination efficiency and increase water treatment capacities. Large amount of specific energy requirement, leading to high operational costs, bio-fouling and less resistance of membrane to chlorine ion presents a big challenge in adopting desalination technologies. These challenges can be addressed by considering the newly emerging nano-materials especially those made from carbon. Carbon CNTs have recently attracted considerable attention for the synthesis of novel membranes with attractive features for water purification. This paper critically reviews the recent progress on the synthesis and applications of carbon CNT based membranes in water treatment. Various synthesis techniques for the preparation of CNT based membranes are discussed. Furthermore, the effect of incorporating CNTs in the matrix on the membrane properties has deliberated in detail. The key issues associated with the synthesis of CNT based membranes for actual applications are highlighted.

Finally, research directions are given to ensure the fabrication and application of CNT membranes in a more effective manner. This paper presents a comprehensive literature survey and review that brings those CNMs into focus which directly participate in desalination processes. The structural and functional properties of CNMs, their fabrication into membranes, their hybridization with polymer membranes are some of their usages in desalination processes which are exploited. The survey and analysis of the available literature shows that CNMs can enhance capacity and efficiency of next generation desalination systems particularly RO and membrane distillation.
Keywords: Desalination, Carbon nano-materials, Bio-fouling, CNMs, MWNTs, RO membrane and Graphene.

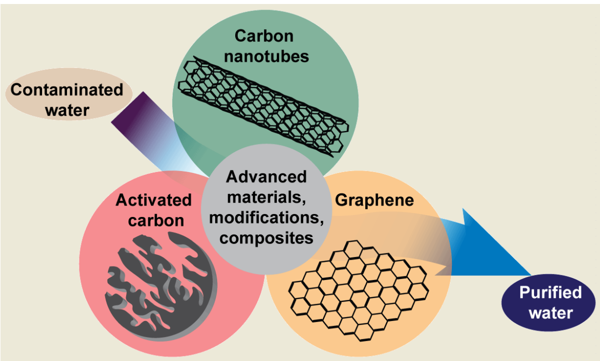
INTRODUCTION

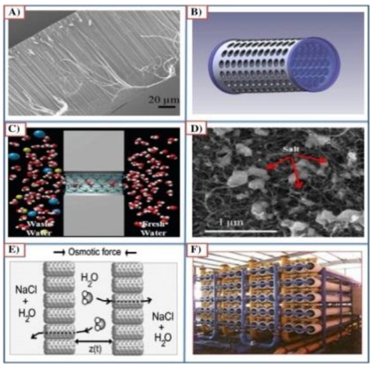
Scarcity of fresh water is among the world's biggest problems of today. Presently, about three billion people on earth are unable to reach clean drinking water [Gilau et al., 2008]. It is predicted that two third of all the countries on the globe will besuffering from water shortage by 2015 [Service, 2006]. The problem of access to safe drinking water is further complicated by climate change, rapid industrialization, population growth, and contamination of existing water resources [Elimelech and Phillip, 2011]. In the ancient times, people determined the purity of water by taste, and this method has been found to be incorrect later on. Nonetheless, their continual efforts in obtaining clean drinking water have led to the development of many innovations that make water treatment more successful today. In present time many methods have been developed to treat and purify water. These methods seek to create a safe water supply free from sediment, minerals, harmful chemicals and microbiological impurities. Among these methods, membrane technology is considered as one of the most important methods for water treatment, and its application is widely expanded all over the world. Although, membrane desalination techniques require high initial setup cost, reuse of salts and permeate partially recompense them [Hassani et al., 2008]. Carbon nanotubes (CNTs) have been studied as a molecular sieve for pervaporation, gas separation, ion exchange, and fuel cell applications, and better separation performances were obtained using those CNTs as additions to polymers [Holt et al., 2009]. Carbon nanotubes have the seamless and tubular structure, and the hydrophobic channel for water passing through. Here we embed multi-walled carbon nanotubes (MWNTs) throughout the polyamide thin film of an interfacial composite RO membrane for desalination. The MWNT-polyamide film might offer much improved membrane performance for reverse osmosis because of its rapid mass transport behavior. First, water molecules appear to flow along the nanochannel of MWNTs, resulting in an energy-saving desalination process. Second, recent numerous simulations on water transport through carbon nanotubes have suggested that not only water occupied the channels, but also the rate of water transport would increase through those channels. Third, if the MWNTs can be grafted with some hydrophilic groups such as -COOH and -OH, it might improve the hydrophilicity of membrane and for better membrane performance.

Rationally designed nanomaterials from synthetic/biopolymers like chitosan, zeolites, graphene, nanometal/oxides, zerovalent metal/magnetic iron, OMS and nanocarbon/carbon nanotube (CNT) utilized in desalination/purification are thoroughly discussed.

Conventional desalination membrane/materials own inherent limitations; nevertheless, designed nanocomposite/hybrid/films address the new challenges/constraints and consequently aid the remediation of environmental/water pollution, thus denoting prospective nanotechnology/science. The morphology and chemical functionality of certain natural/synthetic polymers are altered/controlled rationally yielding advanced membranes/materials, for example, aquaporin, nanochannels, graphene and smart self-assemble block copolymer blends to cater futuristic desalination needs besides superseded conventional membrane limitations too. In a nut shell, advance nanotechnology via electrospinning, track-etching, phase inversion and interfacial polymerization yields structured composites/matrixes that conquer traditional barriers of conventional desalination and supplies treated/purified water.

Rationally designed smart nanomaterials provide myriad scientific and technology growth to desalination/water purification. Still, biomaterials must be explored in this perspective that owes high permeation and low salt rejections in futuristic desalination. Thus, advanced nanotechnology aided commercially viable products/solutions that enhance/replace existing desalination/purification. Certain functionalized nanoporous biopolymeric membranes were found to cater to inherent challenges. Bio-polymer cross-linking fixes usual instability and imposes functionally cost-effective nanoporous biomaterials to be used in desalinations. Overall, rational fabrication highlighted "*design-for-purpose*" unlike *trial-and-error approach* starts with scientific perceptions by knowing inherent barriers, and thus the conceptual design of nanomaterial is proposed, as fed back to desalination problems for thorough usage in water treatments. Nanomaterials' performance must unambiguously be defined in water purifications and need redesigning under failure conditions with "thinking-outside-the-box" prospective as confronted by desalination.





Till now, nanomaterials' rational designing offered more unprecedented opportunities for solving desalination challenges in a sustainable manner. A prospective-ordered designing should owe few aspects namely molecular dynamics/simulation tools to extend problem definition and theoretically needs more multi-functional/all-in-one nanomaterial for effective desalination/water purifications. Therefore, progressive and versatile nanomaterials/devices, which can work under ambient conditions with paramount desalinations/water purification performance, are expected in the near future. Such design-sophisticated material surfaces reversibly counter stimuli via innovative and promising exterior/interior changes and eminent environmental adaptability which displayed myriad functions viz. interfacial pollutant adsorption, omniphobic slippery coatings, responsive particle-stabilized emulsions, and self-healed surface membranes.

Membrane Technology

Membranes have gained an important place in chemical technology and are used in a broad range of applications. The key property that is exploited is the ability of a membrane to control the permeation rate of a chemical species through the membrane. In separation applications, thegoal is to allow one component of a mixture to permeate the membrane freely, while hindering permeation of other components.

Desalination

Many solutions are proposed to solve this grand issue of water scarcity, including repair of existing infrastructure, improvement of water distribution systems, conservation of existing water sources, and rainwater harvesting. Although these solutions can make the existing water resources more efficient, yet they are unable to increase them. Water supply can only be increased beyond hydrological cycle by the application of saline water desalination and water reuse [Shannon et al, 2008]. Since seawater carries the ability to provide unlimited steady supply of water without interfering the naturally occurring freshwater ecosystems, therefore, there has been an increased growth in the number of seawater desalination plants in the last couple of decades [Service, 2006, Schiermeier, 2008, Fritzmann et al, 2007]. By 2016, desalination is expected to provide more than 38 billion m3 freshwater [Schiermeier, 2008]. Desalination processes can be broadly classified into thermal (phase change) and membrane-based processes as shown in Fig. 1. Phase change processes include multiple-effect distillation (MED), multi-stage flash (MSF), freezing, vapor compression, and humidification– dehumidification (HDH), whereas the reverse osmosis (RO), electro dialysis (ED), forward osmosis (FO), capacitance deionization (CDI), and the membrane distillation (MD) are popular membrane-based processes [Garcı´a-Rodrı´guez, 2003]. Among these technologies, RO and MSF are of ultimate importance because they constitute 53% and 25% of total desalination capacity, respectively, Fig. 2 [Schiermeier, 2008, Garcı´a-Rodrı´guez, 2003].

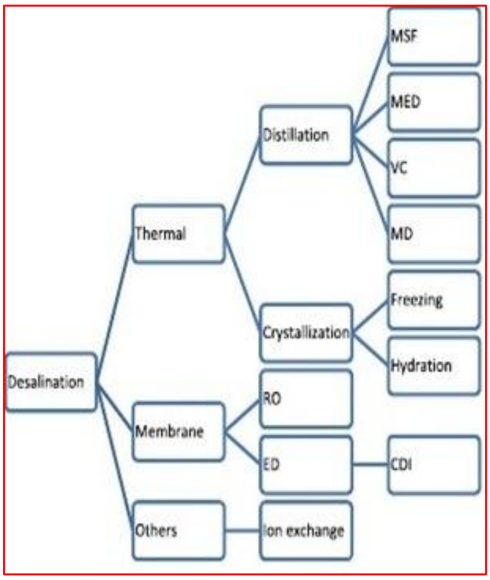


Figure 1. Classification of desalination technologies [Miller, 2003].

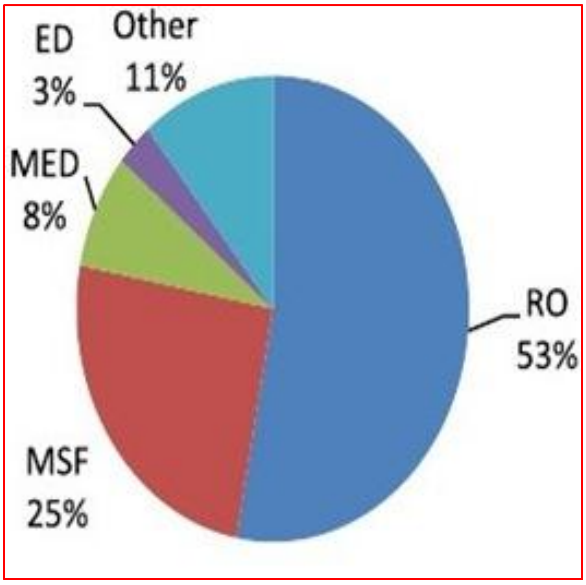


Figure 2. Global desalination capacity by process [Schiermeier, 2008, Garcı´a-Rodrı´guez, 2003].

There is some other various pressure-driven membranes have been developed that separate impurities from water based on the size of the impurity. These membranes are

• **Microfiltration membranes** are semi-permeable membranes with pore sizes ranging from 0.1 to 3 micron and operating pressures below 2 Bar. Microfiltration membranes retain large suspended solids, such as particulate matter, while passing small suspended solids and all dissolved materials.

• **Ultrafiltration membranes** are semi-permeable membranes with pore size ranging from 0.005 to 0.1 micron and operating pressures between 1 and 10 bar. Ultrafiltration membranes retain suspended solids, oils, bacteria, large macromolecules and proteins, while passing most small organic compounds, acids, and alkaline compounds.

• **Nanofiltration membranes** are semi-permeable membranes with pore sizes ranging from approximately 0.0005–0.005 micron and operating pressures between 5 and 40 bar.Nanofiltration membranes retain all solids, bacteria, macromolecules, organic compounds, and divalent salts, while passing monovalent salts, acid and alkaline compounds.

• **Reverse osmosis (RO) membranes** are membranes with pore sizes in the range of 0.0005 micron and operating pressures in RO are generally between 10 and 100 bar. RO membranes retain all solids, bacteria, macromolecules, organic compounds, divalent salts, monovalent salts, acids and alkaline compounds, while passing essentially pure water.

Membrane Technology Advantages

The following are some of the main advantages of the membrane technology.

1. Energy savings:
   - Energy consumption is low since no phase change is required for processing.
2. Membrane processes operate at ambient temperatures and are suitable for processing of heat sensitive products.

3. Reduction of transportation costs:
    - Removing water from process streams can significantly reduce the volume of product (concentrate) to be transported.
4. Low floor space requirement for system.
5. Automation:
    - many systems can be instrumented to automatically start, stop, or begin a cleaning cycle, and
    - System controls can be installed to shut down automatically in the case of pH, pressure, or temperature problems.
6. Low labor intensity and costs.
7. Short start-up time:
- Many microfiltration, ultrafiltration, and reverse osmosis systems can bere-started in less than a half hour.
8. Clean-in-place (CIP):
- Because of the modularity of membrane systems, it may not be necessary to shut down the entire system for cleaning.

Membrane technology disadvantages

The following are some of the main disadvantages of the membrane technology.

1. Fouling:
    - All membrane systems experience fouling;
    - Pre-filtration and other fouling reduction methods are usually necessary.
    - Periodic cleaning is needed to restore flux.
2. Limitations imposed by membrane materials:
    - Chemical compatibility of feed stream and membrane materials, and
    - High cost of certain newly developed high performance membranes (ceramic and metallic).
3. Chemical compatibility:
    - Process streams must be chemically compatible with membrane and system construction materials**.**
4. The water is de-mineralized:
    - Since most mineral particles (including sodium, calcium, magnesium, magnesium, and iron) are larger than water molecules, they are removed by the semi-permeable membrane of the R.O. system Hummer et al., 2001].
    - Removing the naturally occurring minerals also leaves the water tasteless. Many people thus have to add liquid minerals to their R.O. water to improve the taste.
5. The drinking water is acidic:
    - One of the primary reasons R.O. water is unhealthy is because removing the minerals makes the water acidic (often well below 7.0 pH). Drinking acidic water will not help to maintain a healthy pH balance in the blood, which should be slightly alkaline [Kolesnikov et al., 2004].
    - Medical research has also determined that drinking acidic water (as well as other acidic beverages) will often cause a leaching of essential minerals, such as calcium and magnesium, from the body, especially from the bones and teeth, in order to neutralize the acidity.

6. Some critical contaminants are not removed from R.O. water

- While reverse osmosis is effective for removing a variety of contaminants in water, it does not remove volatile organic chemical (VOCs), chlorine and chloramines, pharmaceuticals, and a host of other synthetic chemicals found in municipal water. [Joseph and Aluru, 2008].

Development in membranes

RO is one of the fastest growing desalination technologies because of its lower specific energy consumption. Energy consumption can be further decreased in RO due to the development of new membrane materials, scaling inhibitors, bio-fouling reducers, and energy recovery devices. Upon optimum modifications, RO can save up to 92KWh energy for every cubic meter of freshwater produced when compared to conventional MSF [Fritzmann et al, 2007]. Although, notable advances have been made in the development of RO membranes [Han et al., 2007, Grunwald, 2008, Song, 2009]; yet, future water challenges require more than mere optimization of polymeric membrane materials. Nanotechnology has enabled researchers to create size-selective, well-defined, nanostructured filtration membranes by providing them control over fabrication of nano materials. Unlike polymeric membranes, which carry flexible chains and are unable to form well-defined pores, nano-membranes with size-selective pores at nano meter scale are expected to allow separation of water molecules, while simultaneously preventing the salt ions with larger diameter due to hydration shells [Grunwald, 2008]. For example, hydrated sodium ion is 76nm (diameter) which can be removed by sieving through a membrane having pores smaller than 76nm and bigger than water molecule. Similarly we can also remove volatile organic chemicals (VOCs), chlorine and chloramines, pharmaceuticals, and a host of other synthetic chemicals found in municipal water with the help of Carbon nanotubes.

Nanotechnological Approach

The term “nano” is used for structures and processes which carry, at least, one dimension between 1 and 100 nm. Nano science and technology deals with the preparation and application of structures at nanometer scale. Roughly, a nanometer is a size of 3–5 atoms stalked together and this is a new technology for the scientists working with bulk properties (>100 nm) or at atomic level (<1 nm). Nanotechnology originated due to advancement of probing and fabricating structures at nanometer level. So far, engineers have built the existing infrastructure while working with bulk properties of materials as against chemists and physicists who developed experimental as well as theoretical techniques for probing molecular and/or atomic structure of matter.

Recently developed CNMs have a potential to decrease costs by increasing energy efficiency in desalination processes. The unique physical, chemical, and electronic properties of CNMs, which are due to their hybridization state (structural confirmation), have made them a successful contributor toward research in drug delivery, electronics, structural materials, bio-imaging, bio-sensing, and energy conservation [Thomas and McGaughey, 2009]. Thesingle- and multi-walled CNTs, fullerenes, and graphene are among the CNMs which are successfully applied to various environmental problems [Mauter and Elimelech, 2008]. Recent researches indicate their potential to successfully contribute toward desalination technologies. CNMs are either applied directly or used to modify a material to improve its workability and efficiency.

Carbon Nano tubes

CNTs are rolled-up graphene sheets consisting of carbon atoms and exhibit exceptional mechanical strength, high electrical and thermal conductance, and unique electronic properties. These properties make CNT an attractive candidate for large range of applications including, structural materials, energy storage devices, adsorbents, semiconductors, and other electronics [Baughman et al., 2002, Dresselhaus et al., 1995]. CNTs of diameter down to 1.6nm can be prepared successfully by applying recently developed synthetic procedures [Cheung et al., 2002]. This control over synthesis opened a gateway to the CNT membranes which can be applied in RO systems [Fornasiero et al., 2008]. Molecular dynamics experiments and models suggest that water flux through CNTs can be substantially higher than approximated continuum hydrodynamics [Hummer et al., 2001]. Also, molecular dynamics simulations provide mechanistic understandings of this rapid water transport. Firstly, it was discovered that an ice shell with water chain structure is formed due to confinement of water molecules in CNTs exhibiting stronger interactions between water molecules compared to those between water molecules and walls of CNT [Kolesnikov et al., 2004]. Later, other research revealed that not only hydrophobicity but also atomistic smoothness is also required for rapid transport of water through CNTs [Joseph, 2008]. Recently, curvature of CNT is held responsible for friction coefficient between CNT wall and water molecules [38] as represented in Fig. 3. However, molecular dynamics simulations revealed that interaction energy landscape of CNT with water molecules is modulated by its curvature; thereby, decreasing CNT diameter decreases friction leading to its total extinction at 0.5 nm. Also, simulations indicated that outer surfaces of CNTs are more prone to water friction compared to inner surfaces.

There is some experimental verification for the 4–5 orders increase of liquid flux upon applying CNTs. An interesting feature of this increased flux is its independence of fluid viscosity [Majumder et al., 2005]. This study was performed on water, ethanol, hexane, decane, and isopropane. These solvents were passed through 7 nm CNTs (under 1 bar pressure) and continuum hydrodynamics was applied to estimate flux using vertically aligned CNTs with polystyrene.

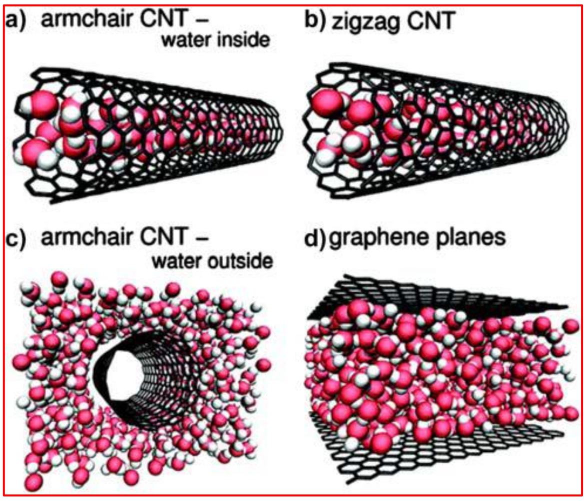


Figure 3. Flow of water through CNT: (a) armchair, (b) zigzag, (c) outside armchair, and (d) between grapheme sheets [Falk et al, 2010].

The similar results were obtained when 1.6nm CNTs were used [41]. But, in these studies, the diameter of CNTs used was large enough to sieve salt ions. Therefore, high salt rejection, due to electrostatic repulsion, was achieved by using membranes which carry chemically modified CNTs. A salt rejection of 40–60% (KCl) and up to 100% ($K_3Fe(CN)_6$) was achieved by using carboxylic groups functionalized CNTs [Fornasiero et al., 2008]. Comparatively higher rejection of $K_3Fe(CN)_6$can be attributed to higher electrostatic repulsion between carboxylic group and trivalent anion. However, this salt rejection decreased upon increasing salt concentrations and reached almost zero at 10mM concentration of KCl, probably, due to smaller electrostatic Debye screening length. Fig. 4 describes the rejection of ions reported by [Fornasiero et al., 2008] when six different salts, having similar equivalent concentration, were attempted to pass through same charged CNTs.

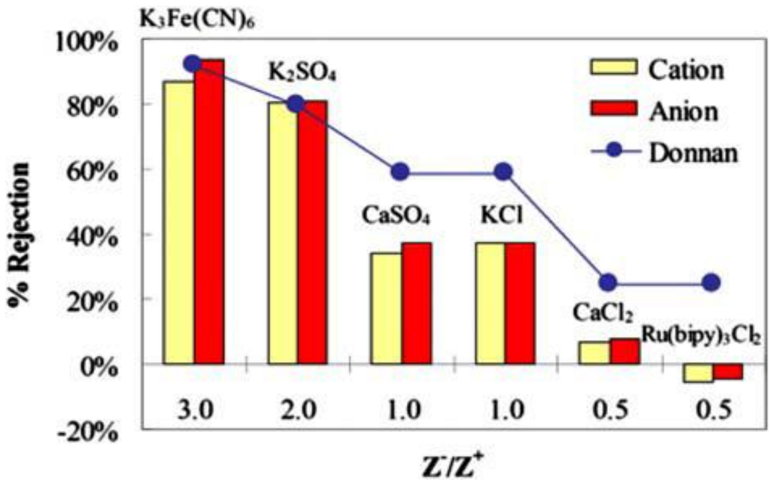


Figure 4. Rejection of six salt solutions that have the same equivalent concentration but different ion valences by charged CNTs [Geim, 2009].

Graphene membranes

Graphene is an atomistic layer of graphite which consists of lattice of sp2-bonded atoms arranged hexagonally [Lee et al, 2008]. It is not only attractive for electronic applications [Lee et al, 2008] due to its unique electronic properties, but also shows high breaking strength [Bunch et al., 2008] and impermeability to small molecules including helium [Bae et al., 2010]. These characteristics of graphene enable it to construct extremely thin membrane with size tunable pores (for molecular sieving) allowing high flux. Also, it can be fabricated on large scale because there is an evidence of synthesizing 30 inch multilayer graphene sheets that have been transferred on roll-to-roll basis. Researchers have recently studied the change in electrical properties of graphene by inducing defects [Zhang et al., 2003]. Their experimental and simulation outcomes suggest that sub-nanometer pores can be generated andcontrolled by electron ion beam, oxidation, ion bombardment, or by doping [Hashimoto et al., 2004, Pomoell et al., 2004, Wei et al., 2009, Suk and Aluru, 2010, Sint and Wang, 2009]. It paved a way to explore the transport of molecules like gasses and ions through the pores in graphene membranes [Sint and Wang, 2009].

Again, molecular dynamics simulations helped in studying the transport of ions through 0.5nm pores in graphene [Garaj et al., 2010]. The graphene used in this study was terminated by either hydrogen or nitrogen.

It was observed that pore in a graphene layer terminated by nitrogen allowed lithium, sodium, and potassium ions, whereas those terminated by hydrogen allowed chloride and bromide ions but did not let fluoride ion to pass. Unexpectedly, smaller ions showed lower passage rates when compared to larger ions. This might be due to strongly bound hydration shells of smaller ions. Also, like protein ion channels, charged terminal groups of pores helped water molecules to move out of hydration layer [Suk and Aluru, 2010]. In another research, a comparison is made between water molecules transport through CNTs having 0.75–2.75nm diameter and 2–10nm length against a graphene membrane of similar diameter pores [Sint et al., 2009] as represented in Fig. 5. The observed flux through graphene was almost double to that of CNTs. The entrance regions of pores were the major contributor toward resistance. These studies show that graphene membranes might be better than polymeric RO membranes for water desalination in terms of allowable flux. However, there is a need of experimental measurements of salt rejection and water transport to verify these expectations [Garaj et al., 2010].

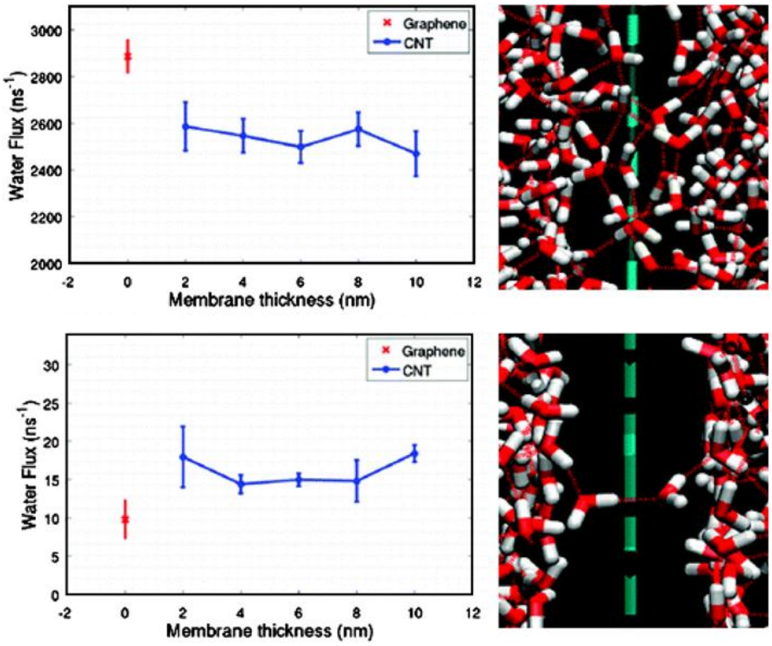


Figure 5. Effect of membrane thickness on water transport across graphene sheet [Garaj et al., 2010].

Carbon Nanotube Based Nanocomposite Reverse Osmosis Membranes are chlorine resistance

It has been find out that polyamide RO membranes have weak resistance to chlorine, causing deteriorated separation performance. Nanocomposite RO membranes containing multi-walled carbon nanotube (MWCNT) were developed to enhance the chlorine resistance of polyamide membranes. The resulting membranes were analyzed and tested to see the desalination performance [Junwoo Park et al., 2012].

In this study, organic/inorganic nano-composite RO membranes were prepared by the interfacial polymerization of MWCNT-dispersed MPDA aqueous solution and TMC organic solution.

Initially, the permeate flux and salt rejection in the conventional PA RO membrane were higher than those in the organic/inorganic nano-composite RO membranes. However, after the exposure to high concentration NaOCl solution, salt rejection in the organic/inorganic nano-composite RO membranes appeared to better that of the conventional PA RO membrane. This implies that MWCNT loading to the PA membrane can enhance the stability against chlorine (or chlorine resistance). In the MWCNT loading range of 0.1–1% (w/v), chlorine resistance of organic/inorganic nano-composite RO membranes was improved as the amount of MWCNT increased.

High-flux thin film nanocomposite reverse osmosis membranes are prepared by incorporation of Multi-walled carbon nanotubes

To enhance the water flux of reverse osmosis membranes, thin film nanocomposite reverse osmosis membranes are prepared by incorporating functionalized multi-walled carbon nanotubes (MWNTs). The functionalized MWNTs are obtained by the treatment of pristine MWNTs with the mixed acid of H_2SO_4 and HNO_3 (3:1 v/v). [Lin Zhang et al.]

Acidified MWNTs are synthesized from pristine MWNTs, and used successfully in the formation of MWNT-polyamide nanocomposite thin films by interfacial polymerization. The results show that modified MWNTs grafted some hydrophilic groups (such as -COOH and -OH), and thereby has better dispersion in the aqueous solution. Compared with the bare polyamide membrane, the MWNT-polyamide membrane has rougher and more hydrophilic surface. The water fluxof MWNT-polyamide membranes is found dramatically improved, which might be owing to the preferentially flow of water molecules through the MWNTs, meanwhile, the NaCl rejection decreases obviously, but PTA rejection is still higher than 98%. This MWNT polyamide thin film nanocomposite reverse osmosis membrane will have a potential application in separation of organic aqueous solution.

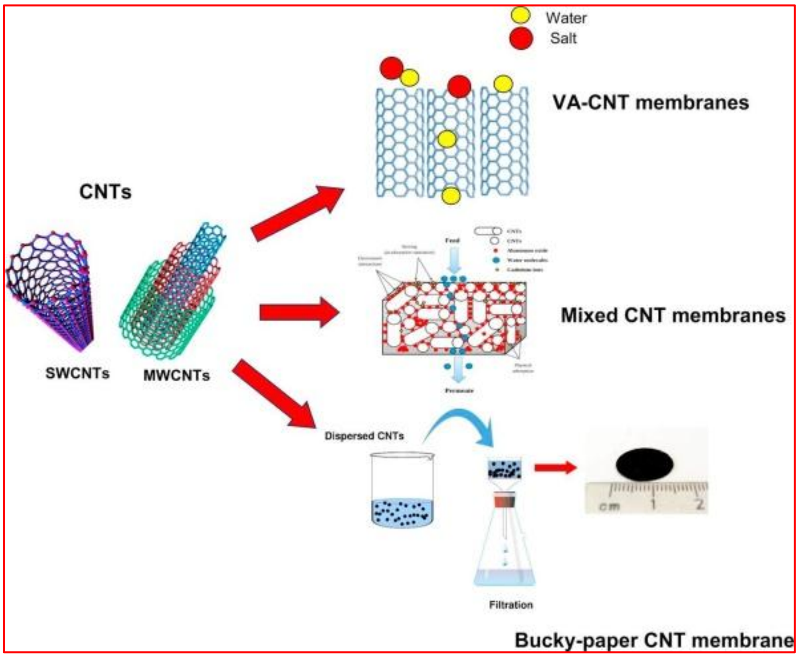


Figure 6. Carbon nanotube membranes for water purification [Ihsanullah, 2009].

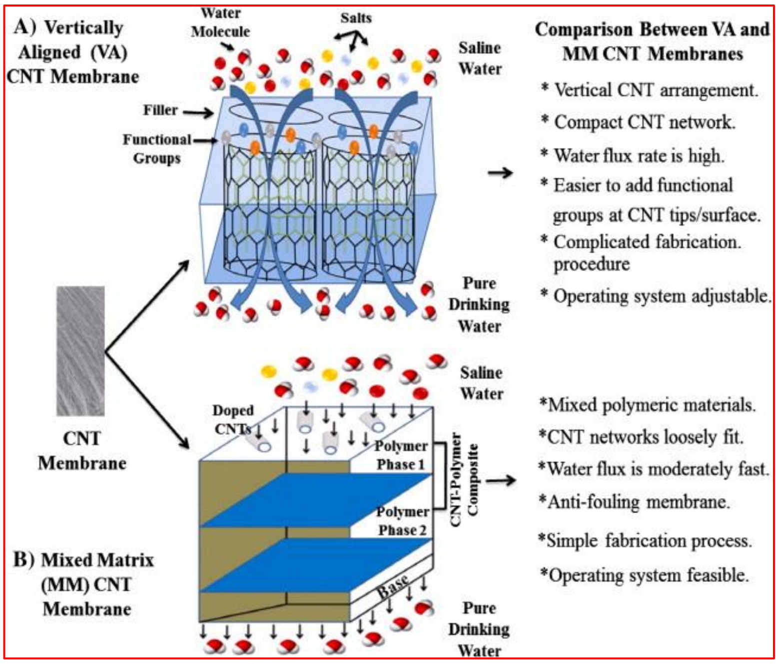


Figure 7. Schematic application of electrospun nanofibrous membranes in various fields [Rajendra].

Futuristic nanomaterials for desalination

Advanced nanotechnologically designed/engineered nanoadsorbents, nanometals, nanomembranes, and photo-catalysts have vulnerable flexibility and adjustability with water treatment systems encompassing assorted micro-pollutants. The compatible existing water treatment processes can be integrated simply in conventional modules. Nanomaterials are advantageous due to their ability to be integrated to various multifunctional membranes that enable both particle retention and contaminant mitigations compared to conventional materials used in water technologies. Auxiliary usages of nanomaterials impart higher process efficiency and higher sorption rates. However, in order to minimize the health risk of nanomaterial's usage in water treatments, several regulatory norms need to be prepared for being adaptable to mass/large-scale utility. Still, nanostructured materials have offered potential innovations in serious contaminants degradation, decentralized water treatments, and point-of-use devices. Nanotechnology assists in wastewater treatments for the mitigation of pathogens, organic and inorganic, heavy metals, and other toxic contaminants using nano-ZnO RO/FO nanofilms and polyrhodanine-encapsulated magnetic nanoparticle that are removed by contaminants up to ppb level. There emerge innovative technologies in nanoscience; yet, many challenges posed by water purification need to be resolved by future researchers.

CONCLUSION

Water pollutants have huge impacts on the entire living systems including terrestrial, aquatic, and aerial flora and fauna. In addition to conventional priority, and newly emerging micro/nano-pollutants, increasing global warming and consequent climate changes are posing major threats to the fresh water availability.

Global warming and climate change are constantly increasing the salinity level of both land and sea water, dwindling the availability of existing fresh water for household, agriculture and industry. This has made it urgent to invent an appropriate water treatment technology that not only removes macro-, micro- and nano-pollutants but also desalinates water to a significant extent. Tip-functionalized nonpolar interior home of CNTs provides strong invitation to polar water molecules and rejects salts and pollutants. Low energy consumption, antifouling and self-cleaning functions have made CNT membranes extraordinary over the conventional ones. We comprehensively reviewed here molecular modeling and experimental aspects of CNT-membrane fabrication and functionalization for the desalination of both sea and brackish water. The increasing demand for clean water, decrease of natural resources of fresh water, and the rise in energy costs are the main drivers for research in improvement of existing desalination technologies. The future desalinating technologies will require nano materials to enhance water permeation flux, bio fouling, chlorine resistance membranes and reduces specific energy consumption as the existing desalination technologies reach maturation. The nanofabrication techniques provide opportunities to understand and develop nanomaterials with extraordinary structural and functional characteristics. This review emphasizes on the application of such carbon-based nanomaterials with a potential to impact future desalination technologies. This paper may provide an insight for the development of CNT based membranes for water purification in future. With their tremendous separation performance, low biofouling potential and ultra-high water flux, CNT membranes have the potential to be a leading technology in water treatment, especially desalination.

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