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Recent applications of nanomaterials in water desalination: A critical review and future opportunities

Sahar Daer, Jehad Kharraz, Adewale Giwa, Shadi Wajih Hasan *

Department of Chemical and Environmental Engineering, Masdar Institute of Science and Technology, P.O. Box 54224, Abu Dhabi, United Arab Emirates

HIGHLIGHTS

- Recent advancements of nanomaterials in water desalination are reviewed.
- Improvements in the last decade have resulted to very high water fluxes.
- Fabrication of nanomaterials minimizes energy requirement and environmental impact.
- Commercialization of membrane desalination using nanomaterials remains questionable.

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ABSTRACT

Given their unique structural and morphological features, nanomaterials have gained considerable attention for their applications in membrane desalination. Recent advances in nanomaterial-incorporated membranes have resulted in membranes with very high water flux and salt rejection, both being sought after in membrane desalination. Nevertheless, the economic feasibility of scaling up such membranes remains questionable. The present paper surveyed the recent published literatures and current studies on nanomaterials and their applications in membrane desalination. The goal of this work was to reveal, through reviewing experimental and computational studies, the potential of nanomaterials in desalination. The paper reviewed three of the most studied nanomaterials in membrane desalination namely; carbon nanotubes, zeolites, and graphene. The investigation included preparation and synthesis of nanomaterial membranes, their properties with respect to desalination, and their applications in membrane desalination. This includes different membrane processes, and opportunities and challenges of those materials in desalination applications. The environmental and economic sustainability of nanomaterials in desalination for future prospects has also been presented.

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* Corresponding author.
E-mail addresses: sdaer@masdar.ac.ae (S. Daer), jkharraz@masdar.ac.ae (J. Kharraz), agiwa@masdar.ac.ae (A. Giwa), swajih@masdar.ac.ae (S.W. Hasan).

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1. Introduction

Freshwater supplies suitable for drinking are in limited supply worldwide especially in dry and arid locations. Alternatives such as desalinating seawater became an option for providing freshwater supplies, however, the process remains energy intensive and more research is needed to enhance its efficiency and sustainability in the long term. Main existing practices for desalination include thermal and membrane processes. Thermal processes for desalination include multistage flash distillation, multiple effect distillation, and mechanical vapor compression. These processes are based on evaporation and condensation principles where water is heated until it evaporates. Vapor is then condensed to produce fresh water while salt is left behind [1]. Thermal processes have in the past provided a major part of desalinated potable water especially in areas where excess heat from power plants is used to desalinate seawater [2]. Thermal processes have many advantages such as relative simplicity required in the construction and operation of thermal plants [3], and the quality of the feed water is not critical which means pre-treatment and operational costs are low [4]. Despite the above-mentioned advantages, they also have many challenges such as scale formation due to precipitation of calcium and magnesium salts on the heat exchanger tubes, corrosion due to the aggressive environment they operate at consisting of seawater and non-condensable gasses, their high energy requirements, and their large footprint requirements in terms of land and material [5]. Hence, those challenges have made the emergence of new processes inevitable. Membrane processes such as reverse osmosis (RO) and electrodialysis offer an alternative for thermal processes. RO today is the most widely used desalination technology globally and it has overtaken conventional thermal technology [6]. Compared to thermal processes, RO energy requirements are low since it performs separation without phase change. RO systems are compact, and thus their space requirements are less and their modular design makes expansion and maintenance an easy option [5]. RO uses selective semipermeable membranes with pore sizes range from 0.0001 to 0.001 μm making it the finest separation membrane process available. With those pore sizes, RO membranes are mostly able to retain all molecules except for water. RO membranes can be made using either polymeric materials like acetate and cellulose or non-polymeric materials such as ceramic [5]. On the other hand, forward osmosis (FO) is an emerging technology that utilizes a semipermeable membrane and natural osmosis phenomenon thereby eliminating the need for pressurizing; but it faces challenges in designing efficient membranes.

Current membrane processes make use of commercial polymeric membrane materials such as thin film composite polyamide and cellulose triacetate membranes for RO and FO. Other membrane technologies make use of poly-tetrafluoroethylene (PTFE) and polyvinylidene-fluoride (PVDF) in membrane distillation (MD). New technologies like capacitive deionization (CDI) utilize carbon based membranes for separating solutes from solvent through an electrosorption and regeneration process. All these membrane separation processes require membranes that perform at high water permeation while maintaining high salt rejection. Current advances in material science led to the discovery of nanoparticles that have been used for many applications ranging from electronics, medical and even desalination applications. This review aimed at reviewing applications of nanomaterials in desalination with respect to three popular nanomaterials which include carbon nanotubes (CNTs), zeolites, and graphene.

2. Carbon nanotubes

2.1. Structural and functional properties of CNTs

CNTs are known as a class of carbon nanomaterials first discovered in 1991 by S. Ijiima and studied thoroughly ever since [7]. CNTs comprise of a sheet of carbon atoms that are rolled into hallow smooth cylindrical tubes that are only one atom thick and have a diameter of approximately less than 1 nm [8]. CNTs have been discovered to have exceptional structural and functional properties such as mechanical, tensile, and electrical characteristics that rendered them a great potential for various technological applications [9]. Two types of carbon nanotubes have been developed and studied extensively since the 1990s and they are single-walled carbon nanotubes (SW-CNT) and multi-walled carbon nanotubes (MW-CNT), which differ by the number of carbon atom cylindrical arrays arranged around the hallow nanotube core (Fig. 1). The properties of each of the two types of CNT vary depending on the atomic configurations of the nanotube cylinders [10]. In general, CNT's unique structural and functional properties such as electrical conduction along with their high aspect ratio (i.e. length to width) and extremely minute size have made them potential candidates for various applications in microelectronics [11], biomedical field [12], and composite reinforcement in polymers [13].

2.2. CNT membranes and applications in desalination

CNTs have been studied for potential applications in water purification and treatment including seawater desalination. This section overviews research undertaken on the important features that CNTs require to render them a viable option for use in seawater desalination, mainly their ability to transport water at a high flux, with maximum salt rejection and minimal fouling on the membranes [14]. Table 1 provides a summary of the applied operating conditions and performance results obtained in recent works involving the use of CNTs in desalination.

Simulation models have extensively been used to study the transport behavior of water molecules in CNT channels [14–19]. Using molecular dynamic simulations of water molecule behavior in CNTs, Hummer et al. (2001) showed that the chain of water molecules cannot only enter and permeate into the CNT, but also experience fast frictionless conduction through the tubes [16]. This is the result of the hydrogen bonding in the chain of water molecules that enter the hydrophobic inner core of CNT tube as well as small interactions between the carbon atoms and water molecules in the interior. More recently, Thomas and McGaughey (2009) studied pressure driven water transport dynamics