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Nano-enabled membranes technology: Sustainable and revolutionary solutions for membrane desalination?

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ABSTRACT

Multidisciplinary, innovative and high values development of high performance, cost-effective and environmentally acceptable separation systems is highly desired to tackle the sustainability challenges that facing current desalination technology. Owing to their versatility and immense potentials to evolve scientific and technical innovations, nanotechnology is probably one of the most prominent strategies that has gained growing scientific and public recognition to provide solutions that can extend the limits of sustainability in membrane desalination technology. This short review provides a brief insight into the roles and prospective of nanotechnology, particularly the nano-enabled membrane technology, to serve as a key element to render feasible solutions for sustainable development in membrane desalination technology. The contribution also highlights the strategies of transforming risk and challenges of this cutting edge technology into competitive advantage in order to timely and efficiently drive values in enhancing the desalination performance, profits and sustainability. The applications of nanomaterials and nanocomposite in membrane desalination are anticipated to foster untapped initiatives and innovation in fundamental science, engineering and technology to spearhead the new wave of leading edge sustainable membrane desalination technology.

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1. Introduction: sustainability of membrane desalination

Continuing population growth and urbanization as well as rapid industrialization are constantly putting pressure on global water demand and resulting in an alarming scenario where accessible fresh water supply is no longer matching the patterns of these developments. Desalination has long served as a feasible option to provide safe drinking water in many deserted areas, coastal regions or remote locations [1]. Despite its versatility in tackling water scarcity, desalination has been unfavorably addressed as the most energy-intensive water treatment technology with undesirable consequences in terms of high economic cost and energy requirements [2]. While the applications of thermal distillation desalination technologies have been majorly restricted by their high power consumption and consequently rather prohibitive, membrane-based desalination has been widely promoted as the key and mainstream desalination technology. With their outstanding attributes for desalination, membrane desalination technology holds undoubtful potential to bridge and connect the dots to battle key issues regarding the current and future water gaps. For decades, the desalination plant designs as well as the guidance and evaluation on the performances of the conventionally used membrane desalination, particularly for seawater reverse osmosis (SWRO), have been

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well established to conform a complete range of industry standards. In the past decade, forward osmosis desalination has also been extensively studied to offer an alternative for leveraging low cost thermal energy [3, 4]. Nevertheless, despite the overwhelming features of these desalination technologies to render the impressive economical operational expenditures of the desalination plant, the impacts of environments and resource depletion associated to the pretreatment and recovery of the membrane-based desalination still deserve growing attentions [5,6]. Although the impact of these issues can be alleviated with good equipment design, operation, practice and maintenance, there are always urgent needs to improve and strengthen the sustainability of this technology [7].

Nanotechnology, which literally refers to the manipulations of materials and processes that are engineered to the molecular scale of 1–100 nm, is an emerging field that poses immense ability to hierarchically construct materials from the bottom up approach to significantly improve the performance as well as add new functionality to the existing products. The evolutions and advancements explored in this field have urged seawater desalination progress as a more economical and sustainable option [8]. In this context, the paradigm shift made by the new approaches and technological innovation based on the new frontier in enabling nanoscience and nanotechnology, although not one size fits all, has advocated the progress of maintaining the sustainability in terms of reduced membrane materials, chemical and energy usage that eventually leads to minimized sources of environmental issues [9]. As membrane transports are inherently nanoscale where the transport of water and salts across the membrane primarily depends on the chemical properties as well as physical structures of the membranes at nano- to microscales, the application of nanotechnology knowledge in the fabrication of so-called nano-enabled membranes is anticipated to counter the limitations of current materials and processes as well as optimize the performance of processes used in desalination. Most importantly, the breakthroughs in this area have also delivered the astonishing tangible outcome: high performance nano-enabled membranes that combine both high productivity and high rejection to meet the hiking research and industry expectations [10]. The unprecedented quantum leaps evidence the versatility of nanomaterials and their nanocomposite to provide the alternative route for sustainable development. This serves the main reason for the industries and stakeholders to be optimistic with the capability of these new generation technology to make a large difference for modern, affordable and environmentally sound remedy for water shortage crisis. Undeniably, the transformation to the era of nanotechnology has the potential to bring the capacity of membrane science and engineering a big step forward for the desalination technology to flourish [11]. However, to precisely gauge the contribution of the nano-enabled membrane towards the advancement and sustainability, one should comprehend how the rapidly proceeding nanotechnology research and commercialization play their roles in providing solutions to the current desalination technology. Along the same vein, glancing back the past efforts towards maintaining the sustainability of the membrane-based desalination technology, few arisen questions must be carefully addressed:

i) Where are we now to contribute remarkable changes to the current sustainable development in membrane desalination?
ii) What can be done to extend the limit of current innovative nano-enabled membrane technology to further harness the economic and performance benefits while co-existing with the desired sustainability?
iii) Is nanotechnology the final piece of jigsaw which serves as the game changer that manipulates the niche and future mainstream of membrane desalination technology?

With the emphasis placed on the applications of nanomaterials in the current trends of desalination research, this review looks at the innovations and strategies of nanotechnologies that have been showcased in the state-of-the-art membrane-based desalination technologies. By referring the correlated questions raised above, the sustainable approaches and significant implications of nano-enabled membrane technology to shape the future of desalination research and industrial competitiveness are highlighted. There are positive signs across the desalination communities that we are maneuvering into the right direction with a growing momentum. In this sense, whether it is a long-term technology or a short path from present technologies, we are certain that when we are ready to leave behind some conservative mindsets in industry and open our arms to new ideas and embrace them, it will be the genuine revolutionary shifts in this field.

2. Innovative nanomaterials: revolutionary solutions for sustainable membrane desalination?

As nanotechnology continues to precede steadily, the primary focus of the research agenda has progressively advanced from the fundamental discovery and characterizations to look into the opportunities of presenting nanotechnology and the resultant nanomaterials as the major key to address the challenges of improving global sustainability, particularly in a wide spectrum of pivotal areas involving energy and environment [12–14]. The application of the conventionally used RO membranes have been severely restricted by the unsatisfactory water recovery and high pressure operation while generating substantial amounts of liquid wastes. As the strongest drivers of the desalination market, industry and municipal suppliers are eagerly looking for the new breakthroughs from the research community to fill the gaps. Therefore, the development of next generation of low-pressure membranes with low energy consumption and heightened salt rejection performance is needed to provide a viable route for sustainable membrane desalination.

To date, a number of advances have been made in the areas of material science for the development of desalination membranes based on nanoparticles and nanocomposites. The plethora of different types of nanomaterials has conferred almost unlimited technological benefits in terms of the adaptation and optimization of new generation membrane for the existing desalination plants. Exciting findings and breakthroughs have been constantly made through the incorporation of conventional nanomaterials such as metal oxides, silica and zeolites to introduce new degrees of freedom in the desalination membrane design [15–23]. Carbon allotropes such as carbon nanotubes (CNTs) [24–27], graphene-family nanomaterials (GFNs) [28–31] and nanodiamonds [32] are emerging nanomaterials that pose huge potential to cope with the sustainability issues of current membrane desalination technology. The frictionless CNT channels with precisely controlled pore entries could simultaneously facilitate the fast transport of water molecules and offer exceptional salt ion rejection capability. Kim et al. demonstrated that thin film RO nanocomposite membranes containing well-dispersed functionalized CNTs possess tremendously high water flux and salt rejection that is comparable to that of without CNTs, which can be attributed to the hydrophobic nanochannels of CNTs [33]. Similarly, the highly accessible nanopores of the graphene monolayers could also promote ultra-fast water flow that surpasses that of conventional polymeric RO membranes. Hu and Mi reported graphene oxide membrane flux that up to 276 LMH/MPa, which was 10 times higher than that of most commercial nanofiltration membranes [34]. Additionally, the abundant surface functional groups have endowed the graphene oxide sheets with hydrophilic nature that reinforced membrane durability associated with their antifouling properties [35]. Recently, biomimetic and bioinspired membranes have been addressed as forefront materials with efficient avenues for membrane desalination [36–38]. A considerable number of recent studies have evidenced the fascinating properties of the nanocomposite membranes consist of aquaporins (AQPs) [39–41]. Xie et al. [40] demonstrated that the incorporation of AQP into polymer vesicles through surface imprinting