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Membrane fouling in desalination and its mitigation strategies

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ABSTRACT

Water scarcity at global level has called for attentions to establish new and innovative technologies that can be tapped to provide sustainable solutions to water crisis. Membrane-based desalination has been acknowledged as one of the promising approaches to resolve the global challenges. Currently, different membrane-based technologies have been deployed worldwide for clean water production. However, despite the great advances made in terms of the permeate flux and rejection, the practical application of membrane for desalination is still limited by the inevitable membrane fouling issue. Membrane fouling is known to be the major culprit to the elevated operating costs due to the deterioration of permeate flux, increasing transmembrane pressure, and frequent chemical cleaning which shorten the membrane's lifespan. This review provides insights into the recent advancement in mitigating membrane desalination fouling. The fouling control strategies which encompass the efforts made in the novel membrane development, feed water pretreatment, and membrane cleaning are highlighted. The advantages and limitations of these techniques are discussed and reviewed based on a substantial number of up-to-date literatures.

1. Introduction

As fresh water is essential for survival as well as for the industrial and economic developments, the global fresh water demand has been accelerating exponentially in the past decade primarily due to the overgrown population and rapid industrialisation in many developing countries [1]. The contamination of available water resources that coexists with climate change has further increased the needs for clean fresh water supply. Currently, more than one-third of the world's population is living in water-stressed regions due to the consequences of the imbalanced fresh water demand and supply [2]. Desalination process has served as a promising alternative to deliver a huge quantity of fresh water. International Desalination Association (IDA) has statistically shown that by 2015, up to 16,000 desalination plants have been installed in more than 150 countries where the production of fresh water has achieved 90 million m^3/day worldwide [3]. Membrane-based desalination technologies, such as pressure driven nanofiltration (NF) and reverse osmosis (RO), osmotically driven membrane processes as represented by forward osmosis (FO) and pressure retarded osmosis (PRO), thermal processes such as membrane distillation (MD), as well as emerging technologies such as microbial fuel cell (MFC) and membrane capacitive deionisation (MCDI) have been well recognised as promising solutions to supply sustainable fresh water and address the water shortage challenge [4]. Out of these processes, RO is undoubtedly the most reliable state-of-the-art technique to produce high quality fresh water from brackish water or seawater [5]. In general, an effective desalination membrane should be simultaneously endowed with excellent physicochemical and separation properties. Some of the other desired features also include high solute rejection and water flux, chemically and thermally stable, and high resistance towards fouling and chlorine attack [6].

Over the last few years, remarkable membrane improvements in terms of salt rejection and permeability have been achieved [7–13]. Nevertheless, membrane fouling is still an inevitable main challenge to reliable membrane performance. In brief, fouling involves complicated phenomena such as adsorption, accumulation, or precipitation of organic and inorganic constituents that take place on the membrane surfaces through different mechanisms under various circumstances [14]. Depending on the membrane natures, feed water qualities and operating conditions, and one or more types of fouling such as biofouling, organic fouling, and inorganic scaling can take place simultaneously. The negative impacts of membrane fouling towards the sustainability of the desalination plants are huge. As membrane fouling could significantly reduce productivity and permeate quality and lead to higher operating pressure, it has been closely associated with poor plant operation and high maintenance cost as the consequences of increased energy demand, additional pretreatment, frequent membrane cleaning, and shortened membrane lifespan [15,16]. For instance, the mitigation of biofouling alone was estimated to cost more than USD 15 billion yearly worldwide in the desalination industry [17]. Despite the

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fact that osmotically driven membrane processes demonstrate several operational advantages which lead to the reduced fouling and scaling susceptibility compared to RO, fouling in FO and PRO is still portrayed as one of the main limiting issues for their practical application [16,18]. In order to mitigate the inborn fouling issue which is specific to membrane-based desalination, numerous approaches have been established and published in the literature. These strategies involve the surface modification and development of novel desalination membranes, pretreatment, and cleaning as well as monitoring and optimisation of operating conditions.

Membrane fouling is remarkably affected by the membrane characteristics. Thus, one of the most straightforward and effective strategies to mitigate fouling is to render antifouling properties through the design of novel membranes. To date, various innovative membrane modifications have been developed to alter and customise the membrane structure and surface properties. In general, the membranes are modified to alter surface hydrophilicity, reduce surface roughness, introduce specially structured polymer through grafting or coating, and introduce new surface functionalities [16,19]. In order to achieve the abovementioned purposes, the modifications can be performed through several strategies. The use of nanomaterials in the formation of inorganic-organic nanocomposite membranes provides the unprecedented opportunities to offer several advantages such as energy-efficiency, low surface fouling, and durability against high operating pressure and harsh condition, without deteriorating the salt rejection ability [20]. Various nanomaterials of different dimensions have been widely applied and carbon-based nanomaterials are currently at the forefront to advance the technology in nano-enabled desalination membranes. It has been well evidenced that carbon allotropes such as carbon nanotubes (CNTs) and graphene oxides can drastically improve the hydrophilicity, water permeability, and antifouling performance of the RO nanocomposite membranes [21–26]. Silver nanoparticles (AgNPs) which is known to be effective against various aquatic microorganisms through their direction interactions with cell membrane has also been extensively explored for the fabrication of antibiofouling properties [27]. Membrane surface modifications which mainly based on polymer grafting [28], zwitterionic coating [29], layer-by-layer assembly [30,31], and polydopamine (PDA) coating [32] approaches are also favourable due to their simplicity and multifunctionality to improve existing membranes that show good desalination potential.

In addition to membrane modifications, feed water pretreatment is also a promising strategy to minimise membrane fouling through the removal of foulants and their precursors such as transparent exopolymer particles (TEP) [33]. Adjustment of water chemical can also be done at this stage. Conventionally, pretreatment is performed via disinfection, coagulation/flocculation, and filtration process. Recently, due to the poor feed water quality and ineffectiveness of conventional methods to deal with the deteriorating feed water, an increasing number of plant owners are switching to the use of membrane based pretreatments such as microfiltration (MF), ultrafiltration (UF), and FO which have been considered as the better replacement. Studies have also shown that the chemical cleaning savings offered by membrane pretreatment can reduce the total water cost, reduce footprint, and provide better on-stream time compared to conventional pretreatment. Practically, the integration of conventional processes in the membrane-based pretreatment line is favourable to effectively remove a wide range of foulants [34,35]. Despite the impressive efforts pursued in the design of novel membranes and the establishment of pretreatment to improve fouling control, these approaches do not guarantee the complete removal of the foulants that present in the feed water. As such, fouling still gradually develops on the membranes where chemical cleaning of the membranes is required over time to recover their separation capacity [17]. Therefore, it is crucial to implement membrane cleaning, either through clean-in-place or ex-situ cleaning, as an integral part of the commercial desalination plants to maintain the process operation. Several types of physical and chemical cleaning techniques such as backwashing, pulsing, forward flushing with air, sonication, and chemical cleaning have been widely applied in desalination plants. Commonly, chemical cleanings are performed using alkaline and acidic agents. The former is used to remove organic foulants and biofilms that are formed on the membranes meanwhile the latter is used to get rid of scaling [36]. On the other hand, physical cleaning such as direct osmotic backwash which involves salt dilution at the feed concentration polarisation layer followed by continuous dilution of the bulk solution and foulant removal can be practically applied for pressure driven and osmotically pressure driven membrane processes without imparting much chemical cost and chemical-induced corrosion on the membrane elements [37,38]. Some NF and RO plants also practice periodic forward filtration mode while performing chemical cleaning to improve the cleaning efficiency [39].

The main objective of this review is to provide a comprehensive overview of fouling in desalination based on the existing literature. As fouling is inevitable in all membrane-based desalination processes, understanding of the roots and causes of this phenomenon will be the key to develop effective strategies to mitigate or remediate the fouling issue. The first section of this review is to elucidate the categories of foulants and their fouling mechanisms. The techniques and characterisations involved in the membrane autopsy are also discussed. The identification of foulant types and their mechanisms is vital to develop optimal pretreatment and cleaning procedures as well as to design novel functional membranes for the mitigation of membrane fouling. In the subsequent section, the state-of-the-art strategies for fouling mitigation based on the recent advances are thoroughly reviewed. Finally, the challenges and issues faced in this field as well as the future outlook are highlighted.

2. Membrane fouling

The fouling of pressure-driven membranes is generally referred to the accumulation, deposition, and/or adsorption of foulants onto the surface of membrane and/or within the membrane pores, which can cause the basic membrane functions to deteriorate over filtration time, including permeate flow, solute removal efficiency, and pressure drop across the membrane [15]. As RO membranes do not have detectable pores compared to microporous membranes, the major fouling mechanism in RO membranes is often associated with surface fouling on the polyamide (PA) layer of thin film composite (TFC) membrane [40]. Nevertheless, depending on the nature of foulants, the fouling of RO membrane can be classified into scaling, biological fouling, organic fouling, and chemical oxidation by residual chlorine. The following subsections provide an overview on the mechanisms of different types of fouling and their impacts membrane surface properties and performance during brackish water or seawater desalination process.

2.1. Scaling

Generally, scaling refers to the inorganic fouling which is caused by the precipitation or crystallisation of inorganic minerals ions such as calcium, magnesium, carbonate, sulfate, and phosphate [41]. Scale formation involves the complex mechanisms of both crystallisation and transport process. The concentration of dissolved salts tend to increase by the factor of 4–10 during the pressure driven desalination processes, which may lead to the crystallisation when their solubility limit is exceeded [42]. Membrane scaling occurs when the ions in the supersaturated solutions crystallise onto the membrane surface through two pathways, i.e., surface crystallisation and bulk crystallisation [43]. The former is mainly due to the lateral growth of the scale and is more prevalent at high operating pressure but low crossflow velocity. On the other hand, the latter refers to the homogeneous growth of the particles in the bulk phase and is more favoured at high pressure and moderate crossflow velocity. Both processes are responsible to the flux decline and surface blockage of the RO membranes. The principle stages of