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Review

# Significance, evolution and recent advances in adsorption technology, materials and processes for desalination, water softening and salt removal

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A B S T R A C T

Desalination and softening of sea, brackish, and ground water are becoming increasingly important solutions to overcome water shortage challenges. Various technologies have been developed for salt removal from water resources including multi-stage flash, multi-effect distillation, ion exchange, reverse osmosis, nanofiltration, electrodialysis, as well as adsorption. Recently, removal of solutes by adsorption onto selective adsorbents has shown promising perspectives. Different types of adsorbents such as zeolites, carbon nanotubes (CNTs), activated carbons, graphenes, magnetic adsorbents, and low-cost adsorbents (natural materials, industrial by-products and wastes, bio-sorbents, and biopolymer) have been synthesized and examined for salt removal from aqueous solutions. It is obvious from literature that the existing adsorbents have good potentials for desalination and water softening. Besides, nano-adsorbents have desirable surface area and adsorption capacity, though are not found at economically viable prices and still have challenges in recovery and reuse. On the other hand, natural and modified adsorbents seem to be efficient alternatives for this application compared to other types of adsorbents due to their availability and low cost. Some novel adsorbents are also emerging. Generally, there are a few issues such as low selectivity and adsorption capacity, process efficiency, complexity in preparation or synthesis, and problems associated to recovery and reuse that require considerable improvements in research and process development. Moreover, large-scale applications of sorbents and their practical utility need to be evaluated for possible commercialization and scale up.



**Contents**



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## 1. Introduction

Water scarcity is recognized as one of the most important concerns in many countries especially in the Middle East at the present and is expected to be escalated over the foreseeable future. Desalination, including the removal of contaminants, salts and other undesirable ions, is widely accepted as a viable technology for supplying fresh water in arid regions since nearly 98% of the world's available water supply is from sea or brackish resources (Alaei Shahmirzadi and Hosseini, 2015a). According to the official reports, there are at least 26 countries without enough water available for daily life as well for agricultural and economic activities (Miller, 2003).

Desalination is recognized as a viable solution for addressing the long-term demands for drinking, agricultural and industrial waters. Commercial desalination technologies can be classified into two main categories (Mezher et al., 2011). Thermal-based technologies such as multi-stage flash (MSF), multi-effect distillation (MED) and membrane-based technologies such as reverse osmosis (RO) together constitute more than 80% of the global desalination capacity currently in operation worldwide (Mezher et al., 2011). In addition, there are other commercial technologies of relatively less practice such as electro dialysis (ED), ion exchange, humidification dehumidification (HDH), vapor compression, capacitive deionization (CDI) which suffer from limitations like insufficient performance, low efficiency, co-production of wastes, and high costs of installation (Mezher et al., 2011; Velazquez-Jimenez et al., 2015). In addition to the importance of desalination technologies for removal of the major contaminants from raw water resources, many attempts have been made by the researchers on the auxiliary processes that can improve the desalination performance including water softening and salt removal as viable steps in the desalination process.

Adsorption is an attractive technology for separation and removal of salts and other ions from water because it can be developed with relatively low costs in addition to providing flexibility and simplicity in process design, operations and maintenance (Alaei Shahmirzadi et al., 2016; Velazquez-Jimenez et al., 2015; Naidu et al., 2017). Adsorption technology and process are largely governed by the type and nature of materials employed as the adsorbent. A variety of adsorbent materials have been examined for desalination, water softening and salt removal such as zeolites (Aghakhani et al., 2013; Kwakye-Awuah et al., 2016), carbon based adsorbents (active carbon, carbon nanotubes, graphene) (Aghakhani et al., 2013; Tofighy and Mohammadi, 2010), magnetic adsorbents (Lehmann et al., 2014) and low cost adsorbents (natural materials (Sepehr et al., 2013), agricultural and industrial wastes (Karnitz et al., 2010; Yan et al., 2016) as well as biopolymers and hydrogels (Sorour et al., 2015)).

Despite extensive investigations on the development of various adsorbents and processes for water desalination, softening and salt removal, to the best of our knowledge, no comprehensive report could be found to streamline the major research and scientific developments as well as to highlight the ongoing trends. The main theme of the present manuscript is to fill this gap through providing an in-depth analysis on the progresses made in the field of adsorption technology for desalination, water softening and salt removal. In addition, the governing mechanisms along with associated isotherms are described. Special attention is given to the achievements in the synthesis, preparation and modification of established and emerging adsorbent materials and processes for desalination, water softening and salt removal from water resources. Also, the characteristics and important aspects of adsorption-based processes including slurry and fixed-bed reactors, capacitive deionization (CDI) and adsorption membrane filtration (AMF) are reviewed and discussed in details.

## 2. Governing mechanisms in desalination, water softening and salt removal

The governing mechanisms involved in desalination, water softening and salt removal can be classified into three main categories:

(1) Mechanisms involving phase change,
(2) Mechanisms involving short-range interactions with selective materials, and
(3) Mechanisms involving long-range electrostatic interactions.

According to the schematic shown in Fig. 1, generally mechanisms involving phase change are appropriate for highly saline waters and are considered as pioneer commercial methods extensively used for water desalination. On the other hand, mechanisms involving long-range interactions have attracted great attentions in recent years and are often employed for low salinity waters (Humplik et al., 2011). Mechanisms involving short-range interaction apply for desalination of aqueous solution with low to moderate salinity. Such mechanisms are not economically attractive for high salinity applications. MED, MSF and freezing are example of phase change methods while RO and ED are examples of short-range and long-range electrostatic interactions methods, respectively.