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Desalination Engineering: Environmental Impacts of the Brine Disposal and Their Control

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Abstract

Freshwater supplies remain more and more in lack corresponding to the increased demand for several human activities. Such difficult circumstances make desalination of saline water an obligation. Desalination to take out water from saline water has been proved as a safe non-traditional water supply. Nevertheless, like any human-founded method, desalination has conducted to several influences on nature. Charged with chemical products, brine is discharged back to nature. Greenhouse gases (GHGs) emissions are liberated to the atmosphere. Brine and GHGs are the most important effects that have been broadly investigated with some attempts accorded to their mitigation and control strategies (M&CSs). This review examines the M&CSs related to the several environmental impacts (EIs) of desalination engineering and focuses on brine disposal. Numerous EIs could be avoided, or at least reduced, by integrating specific design standards and ameliorating applied technologies. The feedwater source possesses a considerable influence on EIs. At the identical degree, desalination engineering possesses an important impact on the EIs linked to brine features and energy consumption. Fresh desalination techniques have depicted decreased EIs relative to traditional thermal and membrane desalination methods. Further, employing renewable and waste energy sources has illustrated a considerable decrease in EIs related to energy consumption.

Subject Areas

Chemical Engineering & Technology

Keywords

Brine Disposal, Desalination, Seawater, Brackish Water, Mitigation and

Control Strategies (M&CSs), Environmental Impacts (EIs)

1. Introduction

Being vital to all manifestations of life, water is an essential resource [1]. Nevertheless, not all water resources obtainable on and in the Earth are easily available for use [2]. Freshwater resources, which are available to use thanks to their low salinity, form only 2.5% of the total water existing on/in the Earth [3]. Only 30% of total freshwater is potable (*i.e.*, 0.75% of the total water on Earth) with 70% as inaccessible resources in the form of glaciers and snowcaps, 30% as groundwater, and 0.27% as surface water [1]. Saline water constitutes almost 97.5% of the total water existing on Earth. It is attainable to nearly all nations; rendering desalination the indispensable choice for securing water supply for water-stressed nations [4]. The present universal desalination capacity (UDC) is nearly 100 million cubic meters per day (MCM/d) from around 16 thousand plants in 175 states around the globe, with the middle east and north Africa (MENA) countries holding around 50% of the UDC [5] [6].

Thermal desalination employing multistage flash distillation (MSF) and multi-effect distillation (MED) has been the principal desalination technique over the 1950s-1970s period [1]. Thermal desalination is chosen for power and water production (*i.e.*, co-generation) and where energy is low cost [7]. Presently, thermal desalination accounts for around 25% of the UDC. Thermal desalination remains largely implemented in the Gulf Cooperation Council (GCC) countries [5]. Membrane desalination utilizing reverse osmosis (RO) and nanofiltration (NF) membranes has been developed in the 1970s-1980s [8] [9] [10]. Actually, RO and NF prevail in the desalination market thanks to their lower energy consumption and modular nature [5] [11].

Thermal desalination possesses the benefit of being appropriate for some circumstances like high-salinity, high-temperature, and low-quality feedwaters [1] [12]. Nevertheless, the prime drawbacks stay the high-energy consumption(thus higher cost) and higher environmental impacts (EIs).Greater EIs are mostly due to greenhouse gases (GHGs) emissions and discharge of hot brine [13] [14]. Otherwise, membrane desalination possesses the merits of lower energy consumption, and (thus lower cost), suitability to a wide range of feedwater salinity (such as wastewater, both domestic and industrial, brackish groundwater, and seawater), and plant size scalability (from few m^3/d to hundreds of thousands m^3/d) [15]. In membrane desalination, the two major different methods of RO and NF furnish larger options for feedwater salinity. This is mostly attributed to the distinction in salt rejection with around 99.5% for RO, whilst it changes for NF from 50% to 90% for mono-valent ions such as Na^+ and Cl^- and up to 99.5% for divalent ions such as Ca^{2+} and SO_4^{2-}. Accordingly, RO runs at high pressure up to 70 bars, while NF runs up to 20 bars [16]. Nevertheless, RO possesses higher pretreatment demands that are not appropriate for high feedwater salinities as the maximum attainable recovery decreases as the feedwater salinity increases. Further, RO remains more prone to scaling and fouling since it is a pressure filtration-based process [17].

Even if thermal and membrane desalination techniques possess an established solidity and engineering maturity, they possess numerous dares like the high-energy consumption in the situation of thermal desalination, and high pretreatment demands in the situation of membrane desalination, in addition to the several EIs [1] [18] [19]. Further to the thermal and membrane desalination techniques, there is a collection of novel and emerging desalination methods, which are presently under expansion. The major reasons for initiating such emerging desalination methods are lower energy consumption, lower desalination price, and several others [1] [16] [20].

Simultaneously with the augmented use of desalination techniques, their EIs have been the focus of attention. Mainly, the EIs are a function of the feedwater source (either seawater or brackish water) and desalination method being used (thermal or membrane desalination) [1] [21]. Taking into account that the seawater desalination (SWD) is taking 61% of the UDC, juxtaposed to 21% for brackish water desalination (BWD), the EI of SWD attracted most of the research concern [5] [22]. Large research projects have been carried out to assess and investigate the EIs of SWD elements like intake and outfall [23], feedwater pretreatment [24], brine disposal and management [25] [26] [27] and GHGs emissions [28]. For all that such comprehensive investigations for the EIs of desalination methods, few researches have been dedicated to the mitigation and control strategies (M&CSs) of these influences [1]. Moreover, such researches were pointed to treat specific effects of fixed steps (for instance, intakes, or pretreatment, etc.). Nevertheless, until now, there is no investigation realized a rating of the numerous M&CSs for all the steps and techniques implied in desalination [1].

Elsaid *et al.* [1] adopted a holistic approach to examining the M&CSs of the numerous EIs of desalination engineering. The approach treats an intake-to-outfall discussion of the effects for each part in the desalination engineering, which is resumed in **Figure 1** [1]. First, Elsaid *et al.* [1] started their discussion with seawater intake and outfall for SWD exploring its effects and mitigation strategies. Second, they examined feedwater pretreatment and diverse chemical products injected for SWD and BWD, investigating procedures to reduce its EIs via efficacious pretreatment and usage of green chemicals. Third, they focused on the desalination process choice and optimization of its effectiveness, along with the process ameliorations to mitigate the related EIs concerning SWD and BWD. The high-energy consumption of desalination technologies possesses a large set of EIs (mostly via related GHGs emissions like CO_x, NO_x, SO_x, and particulate matter (PM)) presenting a massive carbon footprint. Employing renewable energy sources, as well as efficient power production, constitutes an efficacious mitigation tool for the relevant EIs [1] [29].

Brine disposal remains a challenging desalination problem in general and BWD in particular [1] [13]. Strategies to relieve the EIs of brine disposal are

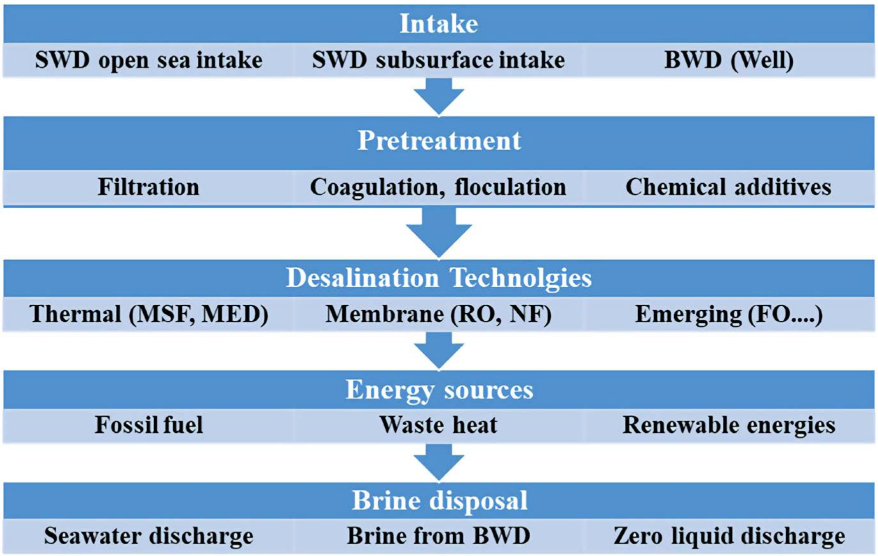

Figure 1. Outlines of the desalination engineering flow according to the intake-to-outfall approach [1].

greatly important because of its volume, representing about 142 MCM/day, *i.e.*, 1.5 times the desalination capability [5]. Compared to ambient seawater, brine ejected from desalination is characterized by bigger salinity and temperature; however, brine is as well carried with all the chemical agents being injected and different by-products being formed [1] [13] [25]. Strategies for relieving the EIs linked to brine disposal have attracted constant interest, with essays dedicated to suggesting a conclusive solution of zero liquid discharge for SWD and BWD [13] [30].

In this work, we present general recommendations to reduce the whole EIs of desalination engineering, with some successful situations to establish the performance of these M&Cs strategies especially those for brine disposal. We start with a brief discussion of the main improvements in the field of desalination engineering.

2. Desalination Engineering

Desalination techniques are numerous and could be mostly categorized into two principal groups following technology maturity: developed and underdeveloped desalination techniques [1]. Developed and well-established techniques could be subdivided into thermal desalination and membrane desalination techniques. Such methods have been applied during decades with confirmed technical and economic feasibility and reliability. Emerging or underdeveloped desalination processes are those that are still at the pilot- or small-scale, with confirmed merits over presently utilized techniques in terms of energy consumption and/or broad feedwater quality. Some of such emerging techniques have been efficiently merged into a hybrid-mode to traditional desalination techniques to reach more advantages, like augmented recovery [31]. **Figure 2** depicts the percentage desa

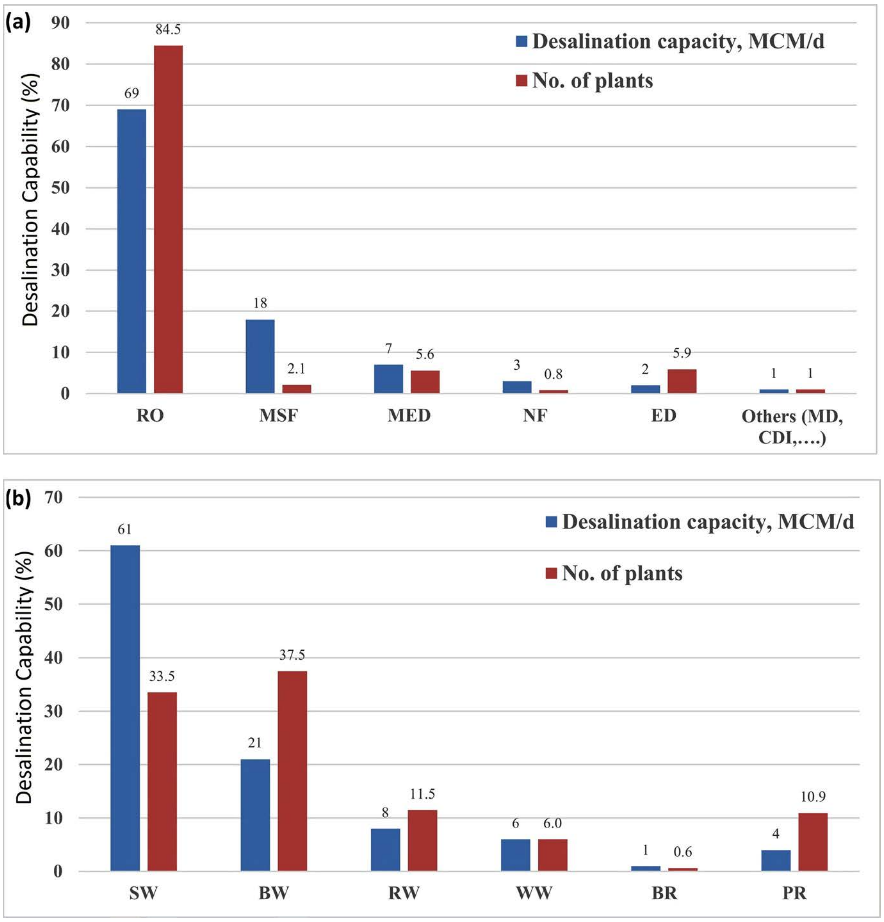

Figure 2. Portion of desalination capability and the number of plants following desalination technology (a) and feedwater source (b) (RO = reverse osmosis, MSF = multi-stage flash distillation, MED = multi-effect distillation, NF = nanofiltration, ED = electrodiyalysis, SW = seawater, BW = brackish water, RW = river water, WW = wastewater, BR= brine, PR = pure water) [5].

lination capability, which is about 100 MCM/d, and the number of plants, around 16 thousand plants, the quota for each process, as well as feedwater source. SWD presents around 61% of UDC, pursued by 21% for BWD, comprising brackish groundwater, pursued by 8% for river water (RW), 6% for wastewater (WW), 1% for brine (BR), and finally 4% for pure water (PR) implementations [5].

2.1. Thermal Desalination Methods

Because the technique purely simulates the natural water cycle, thermal desalination is the earliest utilized method to acquire drinking water from saline water since ancient days [1] [6]. Since the method experiences phase change from liquid to vapor and then reversely from vapor to liquid, thermal desalination is occasionally named phase-change desalination. The method is thermal energy forced, in which the energy in the form of heat is furnished to push the vaporization of a fraction of the feed, which is later condensed as treated water. Thermal desalination has been the major technique in the early era of desalination during the 1950s-1970s [32]. As a rule, thermal desalination stays preferable where: 1) low energy cost, 2) high feedwater salinity and temperature, and 3) co-located with a power plant for power and water production, *i.e.*, cogeneration [33]. Either thermal desalination techniques are through MSF or MED. Seawater is the feed water for almost all MSF plants, and 92% of MED plants [5].

MSF technique is founded on the flash evaporation of the water portion from feedwater. The heated feedwater (that is to say, seawater flashes below decreased pressure in successive stages) ranges 90˚C - 120˚C [1]. The brine from the first stage is fed to the following stage, at lower pressure, so that further flashing is happening without an extra supply of heat energy. The vapor formed in each stage is cooled and condensed, while pre-heating the counter-current flowing feedwater, to ameliorate the energy efficiency and economy of MSF. MSF possesses 18% of the UDC from only 345 plants, *i.e.*, 2% of the number of desalination plants showing that it is mostly utilized for large-scale plants [5].

MED technique stays more efficient from a thermodynamic point of view juxtaposed to MSF, with greater efficiency ratio and lower energy demands [1]. In MED, the sweater is heated to the boiling temperature in the first effect by means of steam. Brine from the first effect is fed to the second effect, where it is heated by the condensing vapor from the first effect, being at lower pressure, and repeated in a cascade of effects at decreased pressure and temperature [1]. Ameliorations in MED have combined it with vapor compression (VC) to elevate its energy efficiency [1]. MED possesses 7% of the UDC from almost 900 plants, *i.e.*, 5.6% of desalination plants [5].

Thermal desalination methods are renowned to be energy-intensive techniques needing both thermal and electrical energy forms [34]. Desalination is very case-specific when it comes to energy consumption, reported as specific energy consumption kWh/m^3 product water. Specific energy consumption is a function of 1) desalination technique, *i.e.*, thermal or membrane, 2) specific technology, *i.e.*, MSF or MED for thermal, RO or NF for membrane, 3) feedwater source or quality, *i.e.*, seawater (SW), brackish water (BW), wastewater (WW), etc., 4) plant design, *i.e.*, design recovery, plant capacity, energy recovery, etc. [35]. MSF plant runs at a temperature > 110˚C and has reported 3.5 kWh/m^3 and 12 kWh/m^3 of electrical and thermal energy equivalent, respectively. Relatively, the MED plant runs below 70˚C and has 1.5 kWh/m^3 and 6 kWh/m^3, almost half that of MSF [36].

2.2. Membrane Desalination Methods

For desalination, membrane methods have been promoted during the 1960s-1970s period, with the major motivations of the augmented energy price [37] [38]. RO remains the primary membrane method, pursued by NF [39]. Osmosis is a natural phenomenon, in which solvent (water in case of desalination) permeates across a semi-permeable membrane (impermeable to the solute) from higher-solvent concentration side of the membrane to the lower-solvent concentration, thus forming a differential hydraulic pressure, named osmotic pressure, which continues till hydraulic pressure difference is equal to the osmotic pressure difference across the membrane [1]. Osmotic pressure is a function of the character of solute, the level of solute, and temperature. Seawater has an osmotic pressure of 27 - 30 bars at ambient temperature [40]. In RO desalination, an external hydraulic pressure higher than that of osmotic pressure difference is applied to the saline water to reverse the osmosis phenomenon leading to water extraction from the saline water by permeation through the membrane [1].

RO desalination was implemented first to brackish groundwater in the late 1960s; then, it was implemented to seawater desalination by the 1980s [32]. Seawater reverse osmosis (SWRO) desalination accounts for 34% of the UDC, *i.e.*, half of RO desalination, while brackish water desalination (BWD) accounts for 19% of the UDC, *i.e.*, 27% of RO desalination as depicted in **Figure 2** [5]. RO membranes are frequently fabricated of two different films, active and selective layer or skin, made of polymeric material either cellulose triacetate (CTA) or thin-film composite (TFC) of polyamide (PA), which is in charge of the semi-permeability properties [8] [9] [40]. The second film is a thick support layer to furnish mechanical strength to withstand the high hydraulic pressure that can go up to 70 bars [8] [9]. The driving force for the RO method is the hydraulic pressure applied to overcome the osmotic pressure; therefore, it changes greatly following the feedwater salinity from 15 - 25 bar for BWD to 60 - 70 bar for SWD [4] [11]. Energy needs vary following the feedwater sources, *i.e.*, brackish water or seawater, with greater energy demands for seawater RO (SWRO) of 2 - 7 kWh/m^3 and less for brackish water RO (BWRO) of 0.4 - 3 kWh/m^3 since it runs at lower pressures [35].

NF membrane was first suggested in the early 1980s to describe a low-pressure RO type of membranes that have a higher rejection of divalent ions relative to that of monovalent ions, with membrane selectivity toward solute of 1 nm cutoff, and hence called *nano* [4]. The NF membranes possess a typical rejection of 60% - 95% toward divalent ions, and 10% - 70% toward monovalent ions, making it appropriate for a broad set of usages [1]. NF membranes are mostly utilized for the desalination of brackish groundwater and softening of hard water [1]. NF has been employed as an advanced pretreatment of seawater for MSF and RO. NF holds almost 3% of the UDC, mostly for desalination and softening of BW and RW, as depicted in **Figure 2** [5].

2.3. Emerging Desalination Methods

In desalination engineering, Research and Development (R&D) stay highly active because of the towering significance of assuring water supply for human activities. The existing traditional thermal and membrane desalination techniques have attracted considerable expansion endeavors during the decades, attaining a constant maturity degree, with present ameliorations leading to lightweight processes enhancements. In desalination engineering, the following revolution is anticipated with the complete expansion of emerging desalination techniques presently at the lab-, pilot-, and small-scale. The motivations for promoting these methods are 1) bigger recovery, 2) lower energy consumption, 3) lower price, 4) large feedwater quality, 5) less EIs, and numerous additional merits [1].

Forward osmosis (FO) is a spontaneous or natural technique that uses the osmosis phenomena; so, it does not require the application of hydraulic pressure [41]. In FO, the normal penchant of solvent (*i.e.*, water) to permeate across the semi-permeable membrane is exploited employing specific higher concentration solutions; thus, bigger osmotic pressure named draw solution. Since FO is a spontaneous method, it is distinguished by lower energy demand, which turns in lower capital and operating costs, with energy consumption as low as 0.25 kWh/m^3 [42]. The first dare retarding the expansion of full-scale FO stays the water extraction from draw solution, which has to be economically and energetically feasible process [1]. The second dare is to promote high water-permeable and selective membranes, with current FO membranes reporting a wide range of 1 - 81 L/m^2h pure water permeability, following the membrane material and draw solution [43].

Electrodialysis/electrodialysis reversal (ED/EDR) desalination has been proposed since the 1950s and employs electrical potential to allow the electrochemical separation of ions [1]. Lately, ED/EDR has attracted notice thanks to ameliorations in electrode material for low salinity feedwater desalination like BWD and pure water treatment [1], or high-salinity brine for brine concentration or minimization [1]. ED/EDR possesses the benefit of using higher suspended and dissolved solid contents feedwater, *i.e.*, high fouling tolerance, higher recovery, and higher durability [1]. ED/EDR possesses a share of around 2% of the UDC, with 60% for BWD and 20% for RW [5]. Energy consumption stays a crucial parameter in ED/EDR operation; with BWD of 7 - 8 mS/cm salinity consumes 1 kWh/m^3 while the concentration of SWRO brine from 60 g/L to 200 g/L has an energy consumption of 3.7 kWh/m^3 [1].

Membrane distillation (MD) is merely an integration of thermal and membrane desalination and is mostly a thermal-driven technique [42]. In MD, feedwater is heated below boiling temperature to give off a vapor that permeates across a hydrophobic membrane that lets only water vapor, but not liquid, which is then condensed and collected as a product [44]. MD technology implies merged heat and mass transfer and happens at ambient pressure, in the span of 70˚C - 90˚C [1]. MD possesses the benefits of 1) total solute rejection; 2) recovery and the energy consumption are not a function of feed salinity; 3) high concentration factor, theoretically up to saturation and; 4) no external pressure, so minimal fouling [45].

Capacitive deionization (CDI) is identical to ED/EDR, since it employs electrical potential as a driving force for attracting iconic species, but utilizing electrosorption of ions into the electrode surface [46]. As for ED/EDR, most of the R&D attempts in CDI are to present fresh electrode material with an elevated capability, lately concentrating on using new graphene-founded material [1] [47].

Adsorption desalination (AD) is so identical to MD in theory, with the distinction of utilizing adsorbent material, like silica gel, rather than a membrane, during adsorption cycle; then, water is stripped or desorbed during desorption cycle [1] [48].

Freezing desalination (FD) is one more emerging desalination technique that possesses identical merits to that of MD and AD [49]. In FD, saline water is cooled down to freeze water as ice, which is separated in a solid-liquid separator, leaving a brine solution [50]. Lately, more regard has been accorded to FD thanks to the evolving in the liquefied natural gas (LNG) industry, which could be employed as cryogenic fluid to drive FD [1].

3. Environmental Impacts (EIs) of Desalination

Desalination has progressed as a credible solution to the dare of secured water supply to numerous underserved nations worldwide. Technology has greatly advanced during the decades, rendering it both economically and technically practical method. While the great value desalination provides to humankind, furnishing the vital water supply, it has been related to several influences on nature. The EIs linked to desalination could be abstracted as follow in association with each stage in the desalination train from feedwater intake to brine disposal:

- Indeed, **Figure 3** illustrates a clear schematic of the inputs and outputs to the desalination technology and its interaction with nature [1].
- Further, **Figure 4** shows the interrelations between the desalination process parameters and relative EIs [1].

4. Environmental Impacts (EIs) of the Brine Disposal and Their Control

4.1. Environmental Impacts (EIs) of the Brine Disposal

In terms of qualitative and quantitative criteria, desalination brine remains a

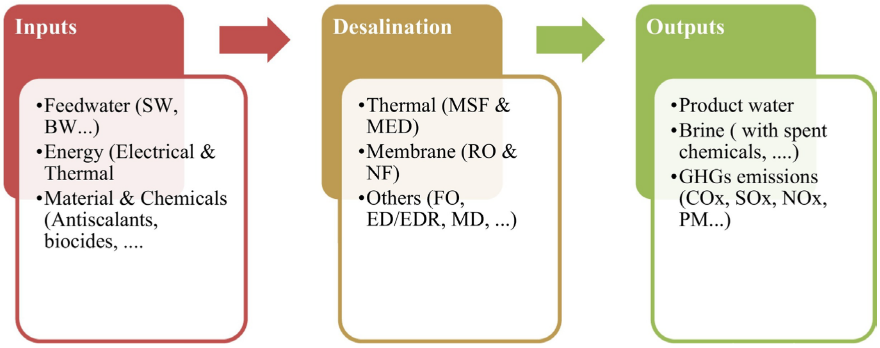

Figure 3. Schematic of desalination technology inputs and outputs (RO = reverse osmosis, MSF = multi-stage flash distillation, MED = multi-effect distillation, NF = nanofiltration, ED/EDR = electrodialysis/electrodialysis reversal, SW = seawater, BW = brackish water, FO = forward osmosis, MD = membrane distillation, GHGs =greenhouse gases) [1].

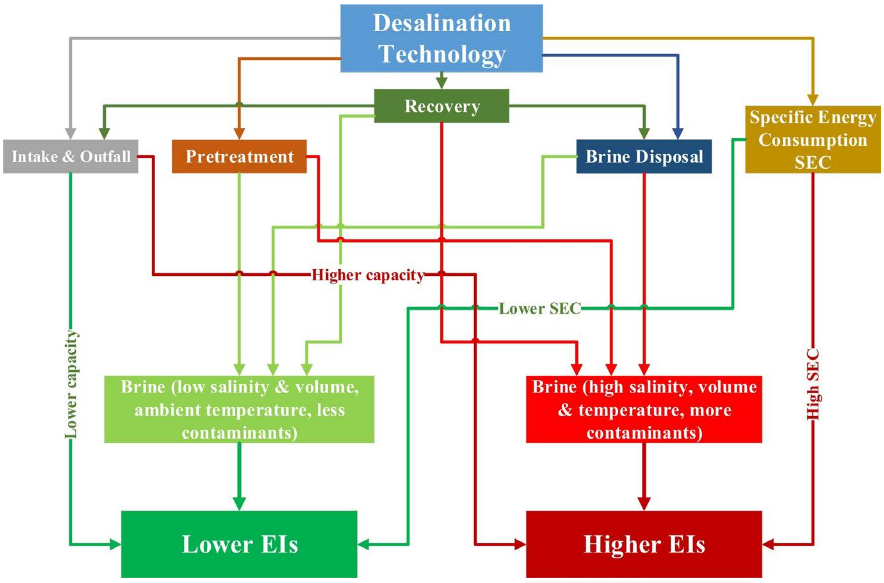

Figure 4. Interrelations among the desalination process parameters and relative environmental impacts (EIs) (Specific energy consumption, SEC) [1].

huge waste stream [1]. The ratio of brine to feed could vary from 1 - 2 for SWRO to 5 - 8 for thermal desalination that possesses a considerable impact on the marine environment at the point of discharge [1]. Linked to brine disposal, the EIs stay mostly affected by the next parameters: salinity, temperature, pH, residual chemicals, reactions by-products, and heavy metals [51]. The brine salinity and temperature are viewed as the main factors to touch the marine environment since brine salinity could attain 65 - 85 g/L and temperature 45˚C - 50˚C [52]. The additional important EI of brine is related to a load of chemical products injected during pretreatment like biocides and biocide scavengers as well as disinfection by-products, which provoke considerable ecotoxicity [53] [54] [55]. Coagulants like aluminum sulfate (alum) [56] [57] [58] and ferric chloride [59] [60] [61] and flocculants [62] [63] [64] are introduced during pretreatment to eliminate suspended and much dispersed solids [65] [66] [67], which end up with filter backwash to be disposed of with brine stream [1]. Antiscalant is injected to dominate scaling due to sparingly soluble salts, thus keep plant productivity, especially at elevated recovery [1]. The brine could carry traces of heavy metals (like copper, chromium, nickel, iron, molybdenum, etc.) as corrosion products of metals employed with corrosion formed by high feedwater salinity [1].

4.2. Mitigation and Control of the EIs of the Brine Disposal

Brine disposal constitutes the closing interaction with nature through brine outfall. The properties of brine to be removed from desalination plant are interconnected to additional plant components (like intake and outfall, pretreatment, and desalination technology). For brine disposal, the definitive M&CSs remain the elimination of the necessity for brine disposal for SWRO seawater, and most importantly, for BWRO through zero liquid discharge (ZLD) process [1] [25] [68]. In ZLD, more water is recuperated, and crucial solid salt is left that could be of beneficial uses or as feed for other plants such as for table salt production, chlorine, and caustic soda [1]. The second solution is to diminish the volume of the brine stream via merging hybrid desalination systems like ED/EDR, which could augment the brine level from 60 g/L to 200 g/L so decreasing the brine volume by almost 2/3 [30].

Table 1 resumes the M&CS for the EIs related to brine disposal. It is worth mentioning that some of the M&CSs are utilized for some other desalination plant components like intake and outfall because of their mutual impact [1].

5. Conclusion

In this work, we presented general recommendations to reduce the whole EIs of desalination engineering, with some successful situations to establish the performance of these M&Cs strategies especially those for brine disposal. We also discussed the main improvements in the field of desalination engineering. From this review, the following observations and conclusions arose:

1) Desalination has a vital contribution to safeguarding human life since it resolves the dare of water supply, especially for water-scarce regions. Desalination remains the first water source for numerous nations like in GCC countries, presenting > 90% of domestic water supply. Thermal and membrane desalination techniques have nearly attained maturity degrees with established technical and economic feasibility [1]. Fresh desalination techniques are presently below expansion with greater productivity and energy efficiency compared to actual

Table 1. M&CSs for the EIs related to brine disposal [1].

Parameters	Environmental impacts (EIs)	Mitigation & control strategies (M&CSs)
Higher salinity & Higher temperature	- Increase salinity and temperature of water body at the discharge point. - Change in water column stratification. - Increase the salinity of groundwater aquifer. - Salinity increase of sediments. - Reduce oxygen solubility and content. - Increase mortality of aquatic life. - Change the structure of the benthic community.	- Apply ZLD technologies. - High recovery desalination. - Brine pre-dilution with wastewater and cooling water. - Efficient pretreatment. - Use subsurface intake. - Use of high-quality materials. - Proper maintenance plan. - Brine treatment for removal of toxic components. - Place outfall in an active hydrodynamic area with high currents.
Pretreatment chemicals & heavy metals	- Change in aquatic diversity. - Change the photosynthesis, metabolic, and growth rates. - Formation of toxic DPBs. - Introduce foreign chemicals. - Increase water turbidity. - Water discoloration due to metal salts added during pretreatment. - Contamination of groundwater aquifer.	

desalination technologies. Nevertheless, desalination generates several environmental impacts (EIs) that should be cautiously dominated.

2) For the numerous EIs related to desalination, mitigation and control strategies (M&CSs) ones are more than important [1]. In this review, we have mainly examined the M&CS for brine disposal. Feedwater source and quality, desalination engineering, and energy source were established to possess an essential influence on the general desalination's EIs. Choosing conveniently the desalination technique stays the central part for reducing the general EIs. Indeed, the desalination technique dictates intake and outfall size, pretreatment demand, energy consumption, and volume of brine disposed of. Mixed desalination technologies, emerging desalination techniques, and employing renewable energies are established to greatly diminish the desalination EIs and viewed as strong M&CSs tools.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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