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REVIEW

A comprehensive overview of environmental footprints of water desalination and alleviation strategies

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Abstract

Desalination is considered the most practiced method to overcome the mounting pressure of water scarcity. Regardless of outstanding performance and manifold advantages presented by desalination, growing concerns about its environmental footprints cannot be overlooked. Reject brine disposal releases numerous antifoaming, fouling resistance, antiscalants, antiturbidity, and corrosion inhibition additives into the marine environment; entrapment, entrainment, and impingement of marine organisms in water intake systems besides intensive energy usage which inextricably interwoven with air pollution, greenhouse gasses emission and noise pollution are major environmental adverse effects of desalination systems. This paper comprehensively explores aforesaid impacts besides offering several case-specific mitigative strategies like water/energy recovery, environmental impact assessment (EIA), CO_2 sequestration, careful selection of land, careful intake and outfall design, brine mining, brine treatment, and application of green desalination technologies to countervail and minimize those undesirable environmental footprints. In this context, several green desalination technologies like functional water channels, gas hydrate-based desalination, energy recovery, hybrid desalination, renewable energy-based systems and temperature swing solvent extraction were discussed. Moreover, several brine mining methods were presented to simultaneously take advantage of the presence of precious materials in the reject brine stream, which can be advantageous from an economic standpoint. To ensure the removal of any potentially negative influences of desalination on human beings and the environment, conduction of stringent monitoring procedures is strongly crucial. Finally, it concludes that with considerable technical advancements in conventional desalination technologies and conduction of cutting-edge desalination systems along with the application of renewable energy sources, achieving a pollution-free and sustainable operation is reasonably sensible.

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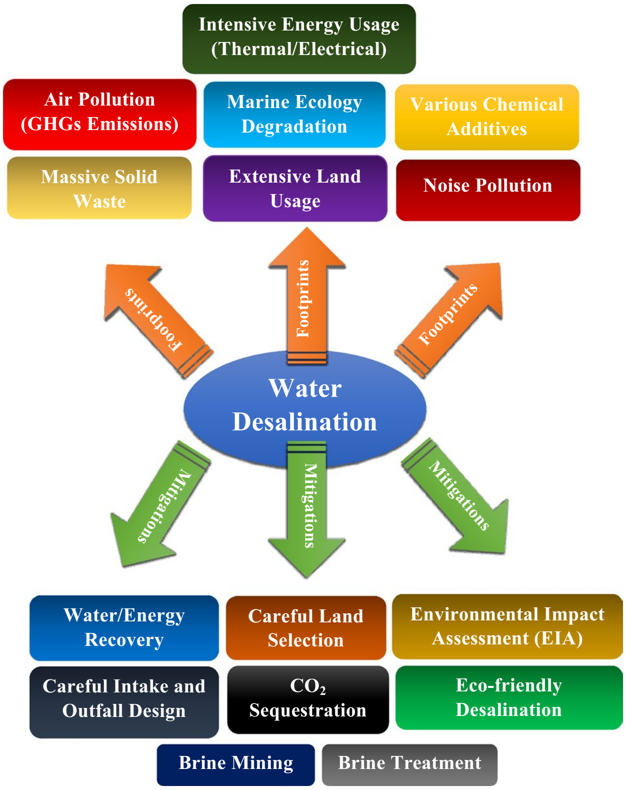
Graphical abstract



Keywords Environmental adverse effects · Desalination · Reject brine discharge · Energy consumption · Greenhouse gasses emissions · Marine pollution

Abbreviations

AD	Adsorption desalination
ED	Electro dialysis
EDR	Electrodialysis reversal
G.Hyd	Gas hydrate
HDH	Humidification de-humidification
I.Ex	Ion-exchange
MD	Membrane distillation
MED	Multi-effect distillation
MSF	Multistage flash
MVC	Mechanical vapor compression
NF	Nano-filtration
RO	Reverse osmosis
RES	Renewable energy source
WH	Waste heat
GHGs	Greenhouse gasses
TDS	Total dissolve solids
WHO	World Health Organization
TSSE	Temperature swing solvent extraction
LCA	Life cycle assessment
ZLD	Zero liquid discharge
MLD	Minimum liquid discharge
PRO	Pressure retarded osmosis
PV	Photovoltaic
TFC	Thin-film composite
BWRO	Brackish water reverse osmosis
SWRO	Seawater reverse osmosis
LNG	Liquefied natural gas
EIA	Environmental impact assessment

Introduction

Water shortage is among the disconcerting challenges of human beings all over the world. Although the earth is a water-abundant planet, potable water for human usage is extremely prohibited because of the hypersalinity of available ocean and sea waters. Regardless of this inherent challenge, climatic variations and some anthropogenic activities like population growth, economic advancements, overexploitation of available resources, and industrialization of different technologies heavily contribute to the serious deterioration of the water depletion issue (Panagopoulos and Haralambous 2020a; Ihsanullah et al. 2021). The cumulative effects of aforesaid formidable barriers gradually propel human beings toward facing extreme water-related problems in the imminent future. In this context, for overcoming these challenges and ensuring the supply of enough volume of freshwater for human consumption and industrial activities, exploring cutting-edge desalination technologies is absolutely crucial. Desalination is a reliable and effective solution for satisfying the ever-increasing demand for freshwater (Elsaid et al. 2020b).

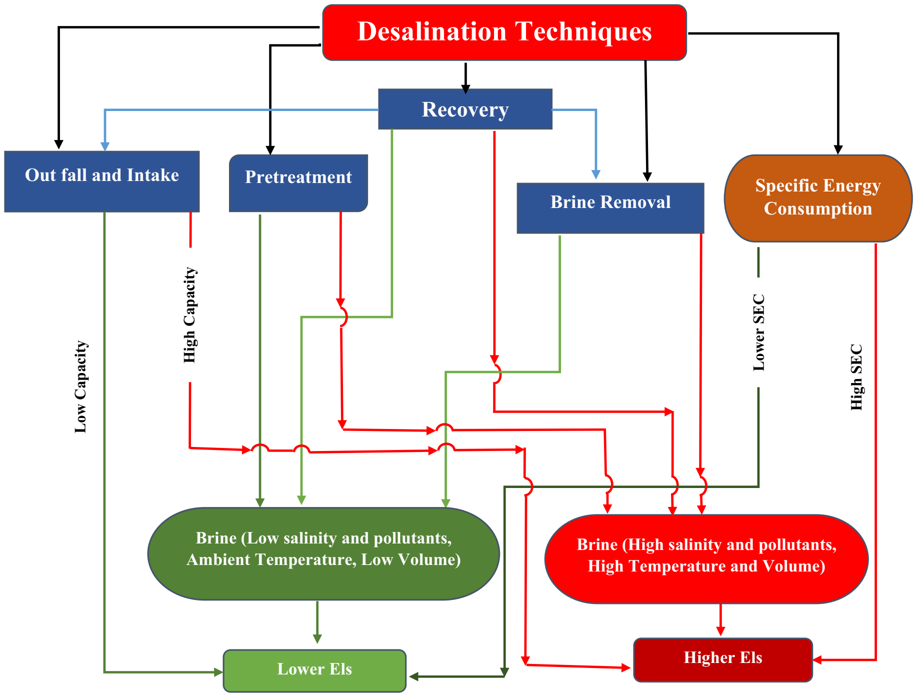
Despite the outstanding benefits of desalination for human beings regarding the supply of fresh drinking water, definitely, just like any other industry and technology, it has some potential environmental and socio-economic effects which must be taken into the limelight. One significant environmental effect of desalination drives from discharging of the reject brine stream since it is hypersaline and might contain hazardous chemicals like H_2SO_4, NaOCl $AlCl_3$, and $FeCl_3$ from different desalination systems (Panagopoulos et al. 2019). It is common that brine to be discharged into the marine ecology and as a result different environmental concerns have emerged. Moreover, the desalination industry is energy-intensive, which is supplied by the application of fossil fuels. The adverse effects of this energy source are emissions of greenhouse gasses (GHGs) and air contamination (Al-Shayji and Aleisa 2018). It is worth mentioning that environmental effects can emerge in the operating and construction of desalination plants. In addition, they are considerably reliant on the feed water source and plant location.

So far, various review papers concerning the impacts of desalination on the environment (Lattemann and Höpner 2008; Roberts et al. 2010; Miller et al. 2015; Ameen et al. 2017; Lior 2017; Shemer and Semiat 2017; Jia et al. 2019; Sola et al. 2020) have been published. However, there are limited review papers that comprehensively discussed all dimensions of adverse environmental footprints of the desalination systems besides presenting recent and state-of-the-art mitigation strategies for removing barriers and reaching a pollution-free desalination technology. Also, a critical evaluation of current and prospective environmental effects of desalination and alleviation strategies for enhancing the sustainability of this on-demand technology is inevitable. Hence, this review paper explores and analyzes all possible dimensions of desalination effects on the environment besides presenting several alleviation measures for properly overcoming its serious challenges for bridging the above-mentioned technical gaps. Attaining detailed and full-scale knowledge concerning the adverse environmental effects of desalination will equip researchers with a potent tool for the conduction of large-scale and green desalination systems in the imminent future.

Overview of environmental footprints of desalination

Because of the ever-increasing desalination facilities across the world, concerns over environmental adverse effects driven by them are being rapidly increased (Fane 2018; Loganathan et al. 2019; Esrafilian and Ahmadi 2019). The main adverse environmental effects of desalination

Fig. 1 Schematic of interrelations between the desalination systems and environment. Reproduced from Elsaid et al. (2020c)



are brine-related contamination, GHG emissions, intensive energy usage, noise pollution, land usage, and construction-related effects (Ihsanullah et al. 2021). Figure 1 clearly presents the interactions of desalination methods with other critical stages like brine disposal, energy usage, pre-treatment, and intake/outfall considering environmental effects (Elsaid et al. 2020c). For instance, by lower intake and outfall capacities and lesser brine volume, the highest recovery will be achieved, hence decreasing the respective environmental effects. In the same way, a high energy-performance desalination system can be reflected by the lesser specific energy usage, which as a result decreases the environmental effects related to energy consumption like GHG emissions. It is evident that based on the type of desalination technology, pretreatment requirements will heavily be influenced as in comparison with membrane-based desalination systems, thermal-based desalination needs lower pretreatment and in turn different ecological impacts (Elsaid et al. 2020c).

Intensive energy usage and air quality

Because seawater desalination utilizes both electrical and thermal energy for its operation, it is regarded as an energy-intensive process (Mannan et al. 2019; Heihsel et al. 2019). Intensive application of energy is mainly associated with fossil fuel burning, electricity generation, plant lighting, freshwater, and brine transportation (Ameen et al. 2017). The efficiency of each desalination technique and the rate of feedwater salinity are two major parameters that determined the extent of energy consumption. Nowadays, because of the significant capital costs associated with applying renewable energy sources (RES), the number of desalination systems powered by them is remarkably low (lower than 1%) (Mahmoudi et al. 2017). Figure 2 presents the percent contribution of RES-based desalination systems. The largest one powered by RES is in Saudi Arabia with an energy usage of 3.7 kWh/m^3 using photovoltaic RO (reverse osmosis) and with a capacity of 60,000 m^3/d which is 24 times low compared with the largest desalination system operated with fossil fuels (TAQNIA 2019). Another notable problem is their availability. For instance, countries with lower solar radiation like Norway (1.95–3.05 kWh/m^2) in comparison with countries with significant solar radiation like UAE (5.72–6.18 kWh/m^2) (Atlas 2020). Also, the consumed fuel for the generation of energy and the accidents related to fuel transportation are considered indirect negative effects of intensified energy on the environment. It is worth mentioning that these effects might be redoubled when their cumulative effects are considered together.

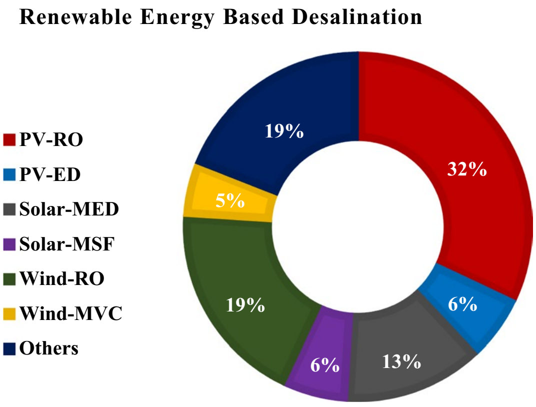


Fig. 2 Desalination systems integrated with RES. Adapted from Mito et al. (2019)

The air pollution initiated by desalination plants is typically significant because the emission of GHGs, primarily CO_2, acid rain gases, and other air contaminants produced during the production of electricity or steam from fossil fuels heavily influences the quality of air and accelerates global warning remarkably (Amy et al. 2017). Generally, the emissions of GHG and air contamination are proportional to intensified energy usage. Nevertheless, GHG emissions rely on the applied energy production method and the form of consumed fuel; hence, they are case-specific (Elsaid et al. 2020b). For instance, in MSF (multi-stage flash) systems, the major sources of SO_2 are the energy stations and desalination burners as they typically consumed significant sulfur-based fuels (Al-Mutaz 1991). The emissions of CO_2 in RO, MED (multi-effect distillation), and MSF systems are typically between 1.75–2.79, 7.01–17.6, and 9.41–25 kg-CO_2/m^3, respectively (Mezher et al. 2011). Figure 3a and b demonstrates related GHGs and the amounts of CO_2 emissions of different desalination technologies according to 1 m^3 product water, respectively (Raluy et al. 2005). In comparison with RO, the major commercial thermal-dependent methods like MED and MSF presents at least ten times higher GHG emissions, which indicate their harmful effects on air quality. Nevertheless, these emissions can be decreased substantially by the application of waste heat to satisfy energy requirements and RES.

Effects on the marine ecology

Waste disposal and desalination-derived side-products in brine

Substantial volumes of reject stream are considered the major undesirable disposal generated from various desalination systems. Figure 4 presents brine production and total global share by distance to coastline (Jones et al. 2019). This reject stream drive from thermal desalination systems usually has significant temperature and contains different chemical wastes applied during desalination like solvents utilized for anticorrosion, antifoaming, and antiscaling goals besides various side-products and heavy metals. These disposals might have potentially negative effects on marine community creatures (Frank et al. 2019; Cambridge et al. 2019). Hence, they can harmfully change physiological conditions, metabolic rates, and diversity of living flora and fauna or physicochemical properties of the environment like dissolved oxygen (DO) level, turbidity, salinity, temperature, and chemical composition (Kress 2019a). The availability of heavy metals in the disposal sites is primarily related to thermal desalination systems, which, because of the significant process temperatures, might lead to corrosion of different metallic facilities. Especially, heavy metals like copper and nickel might exist when their alloys in pumps and heat exchangers undergo wear and tear (Panagopoulos and Haralambous 2020b). Nevertheless, adverse effects of these heavy metals in membrane-based systems like FO (forward osmosis) and RO are usually below critical levels because non-metallic materials like polymers are predominantly employed for their constructions (Nagy 2019).

The seawater desalination produces a reject stream, which usually includes significant TDS varying from 66,000 to 80,000 mg.L^{-1} (Miller et al. 2015) and might be increased in both salinity and temperature. Moreover, the reject stream can contain chemical wastes used in the pre-treatment stage of seawater. To get rid of this reject stream derived from seawater desalination, the most widespread solution is seawater discharge. It might have several secondary undesirable effects on the marine ecosystem when dispose on quite sensitive environments (Roberts et al. 2010). However, these effects are predominantly site-specific and heavily rely on the disposal mode and the physicochemical properties of the reject stream beside the hydrographical and biological features of the target medium. For instance, in comparison with the open-sea exposed areas, surrounded and shallow sites with plentiful marine species may be greatly influenced by brine (Lattemann and Höpner 2008). Different laboratory bioassays validate the negative impacts of brine properties especially salinity levels on various organisms like phytoplankton, microbial communities, and seagrass (van der Merwe et al. 2014; Belkin et al. 2015). Furthermore, brine with extreme salinity levels and temperature decreases the DO levels in the receiving body, which has some serious negative effects on marine ecosystems (Ahmad and Baddour 2014). Moreover, various investigations have

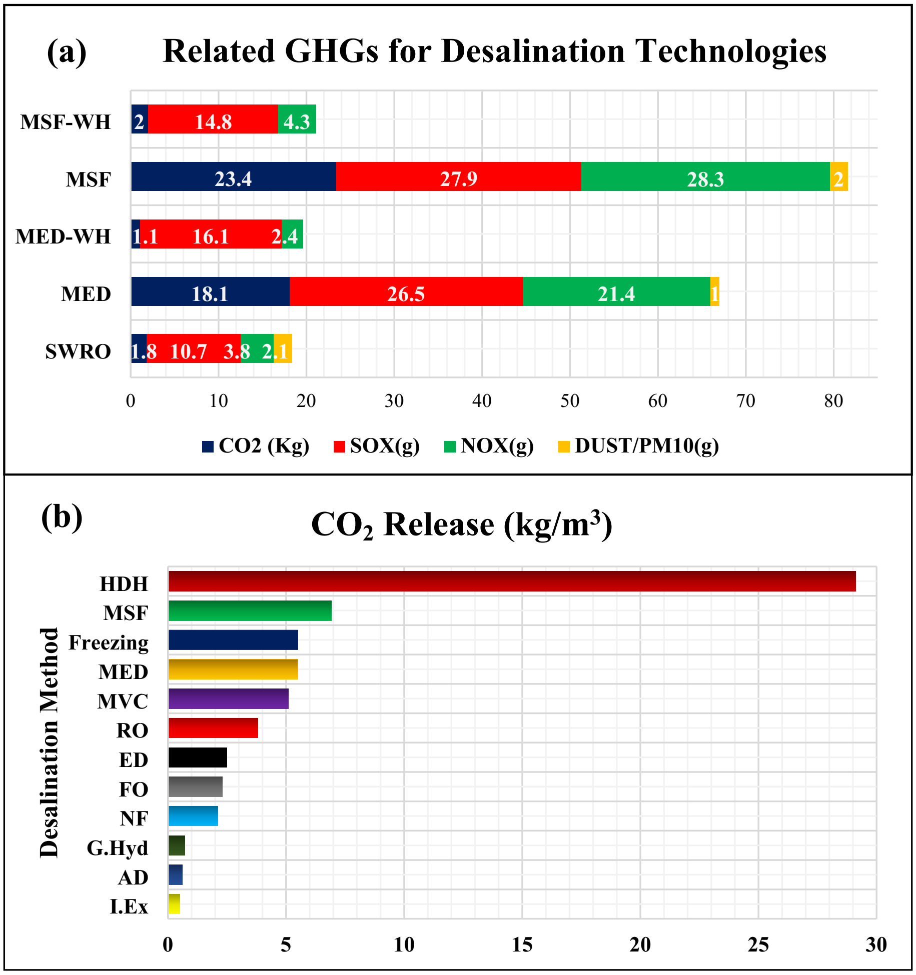


Fig. 3 **a** Related GHGs of different desalination technologies according to 1 m^3 product water based on (Elsaid et al. 2020c; Raluy et al. 2005), **b** CO$_2$ release by different desalination methods based on Youssef et al. (2014), Mehmood and Ren (2021)

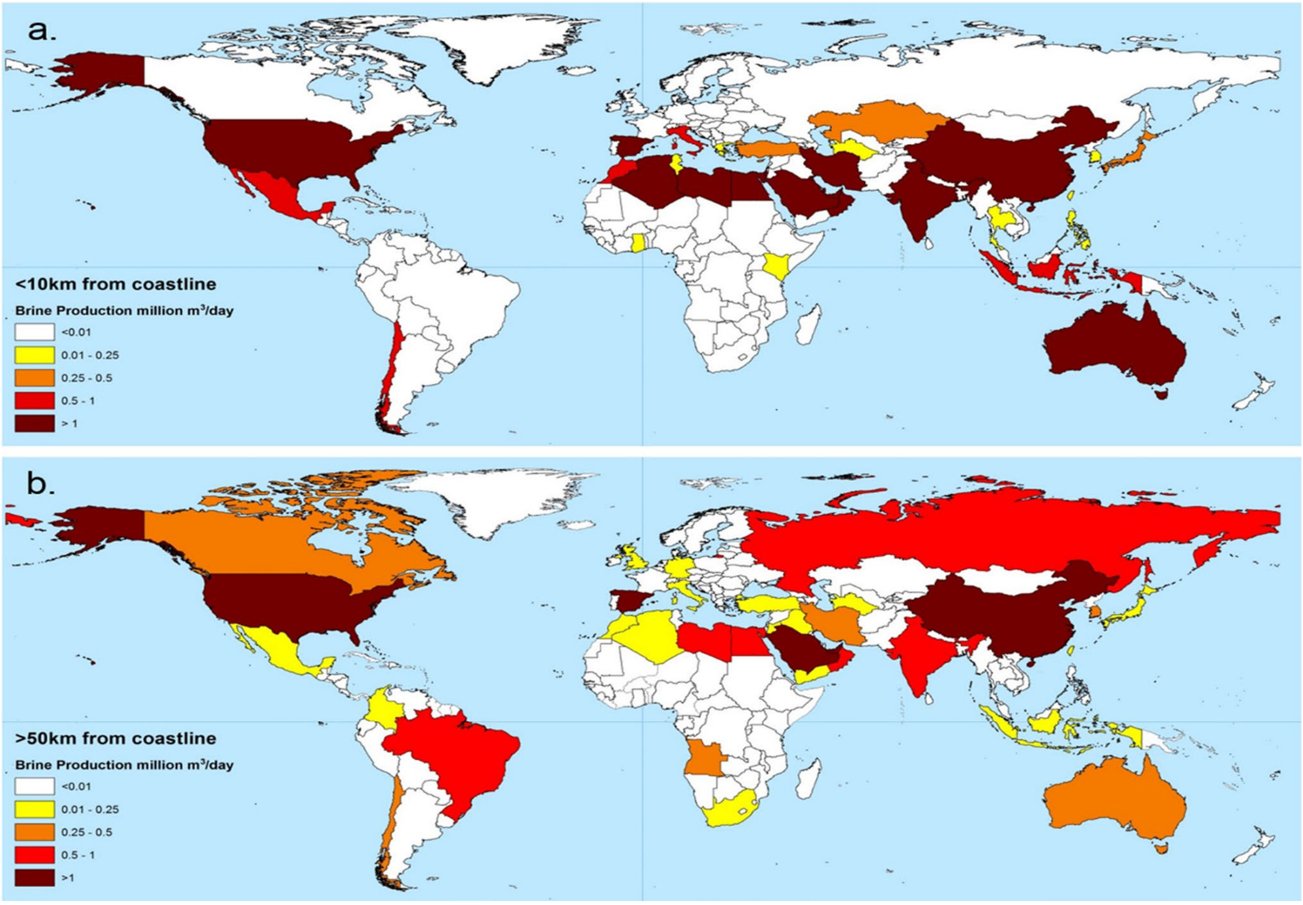


Fig. 4 Amount of brine generated by each country at a distance of **a** < 10 km and **b** > 50 km from the coastline. Reproduced from Jones et al. (2019)

explored the effect of brine disposal on seagrass species like Cymodocea nodosa or Posidonia oceanica. According to the experimental results, salinities over 39.1 mg.L^{-1} decrease seagrasses vitality regarding leaves premature senescence, necrotic spots, and leaf growth. Moreover, around half of seagrasses perished during 2 weeks when Posidonia oceanica was opened to the salinity of 45 mg.L^{-1} (Fernández-Torquemada and Sánchez-Lizaso 2005). The harmful osmotic shock is the most remarkable effect that might occur on marine organisms like seagrass, algae, plankton, fishes, etc., which is because of the irrevocable dehydration of their cells (Abushaban 2019). Due to dehydration, turgor pressure decreases, which can cause long-term extermination of the marine organisms (Belkin et al. 2017).

Temperature and salinity are critical features of brine that directly influence the abundant diversity of marine organisms. In comparison with seawater, the salinity level of concentrate disposal is about twice (Baalousha 2006). The cleaning and maintaining method of instruments, pretreatment and post-treatment process, freshwater production standards, quality of feed water and applied technology are some of the major parameters, which directly determine the properties of brine. The concentrated disposal with significant temperature and salinity levels can remarkably disrupt the diversity and composition of marine creatures in the disposal location (Xing et al. 2019). The hypersalinity might negatively influence the underwater meadows, coral reefs, and green seaweed (Petersen et al. 2018; Cambridge et al. 2019; Kenigsberg et al. 2020). The environmental and hydrogeological properties of the site significantly affected the extent of hypersalinity on the marine organisms. Table 1 presents different brine disposal methods briefly (Panagopoulos et al. 2019). There is not any discharge strategy without disadvantages, and each of them has its own challenges. For instance, the discharges of surface water have a direct adverse effect on the marine ecology, land usage can merely be employed for limited volumes of brine and evaporation pond is a cost-prohibitive technique because significant footprint area, effluent disposal, and deep-well injection are not proper for countries with a significant rate of seismic activity (Panagopoulos et al. 2019). Moreover, since the brine controlling process is cost-prohibitive, great

Table 1 Brine discharge methods Based on Panagopoulos et al. (2019)

Approach	Environmental Effects	Cost ($/m^3 brine rejected)
Land application	Soil salinization	0.74–1.95
Deep-well injection	Groundwater contamination and soil salinization	0.54–2.65
Surface water discharge	Marine ecology contamination	0.05–0.30
Evaporation pond	Soil salinization and groundwater contamination	3.28–10.04
Sewer discharge	Prevention of bacterial growth in the wastewater remediation plant	0.32–0.66

share of the equipment discharge untreated brine into the sea or ocean. Applying international environmental regulations will effectively confine traditional discharge systems like deep-well injection, surface water disposal, or seawater disposal (Alobireed 2014). As a result, despite the application of brine discharge methods, it might have an environmental negative effect.

The extent of the desalination effect on the marine ecosystem relies on biological and hydrographic conditions of the disposal area and physicochemical properties of reject brine. Shallow, closed, and semi-closed areas, with remarkable biodiversity of marine organisms, are vulnerable to heavier effects on the overall health condition of the ecosystem. In the semi-closed locations of the sea, like the Mediterranean and the Red Sea, a variation in the salinity level can be remarkable (Williams and Follows 2011). In contrast, in areas with numerous ocean currents like Australia, insignificant effects have been posed to the marine ecology (Water 2005; Outfall et al. 2015).

Limited studies have evaluated the brine effect on benthic species like polychaeta and echinoderms (Fernández-Torquemada et al. 2013; Del-Pilar-Ruso et al. 2015). According to the results of recent investigations, concentrated brine streams can greatly affect benthic bacteria in localized and specific areas, where local stressors like eutrophication and increased water temperature and the discharge facilities have changed the plenty and biodiversity of these habitats (Frank et al. 2017). Petersen et al. found various ranges of salinity in coral reef-building habitats and their findings demonstrated that intensified salinity rates like 10% higher than ambient level changed the visual appearance and physiology of corals (Petersen et al. 2018). Apart from the type of marine organisms, a broad range of species may transiently adjust themselves to unusual temperature and salinity levels; however, when opened to extreme and undesirable situations, the diversity of flora and fauna will be strongly influenced, and in several conditions, variations in the environment might attract other scarce organisms in the area under typical situations. Kress et al. detected that the reject stream can elevate the seawater temperature up to 0.7 °C (Kress et al. 2020).

The temperature of reject brine (higher than ambient temperature) from thermal desalination systems might have different adverse effects on the marine lifecycle because the toxicity rate of metals and chemicals is typically increased with increasing temperature (Ahmad and Baddour 2014). Even though little changes in the rate of temperature and salinity may not pose any stringent effects on most organisms, nevertheless, constant exposure to undesirable conditions may be lethal for them (Lattemann and Höpner 2008; Gude 2016). As different studies reported the adverse effects of hypersalinity and temperature on the sensitive ecosystem and benthic communities that are available in the seawater (Kenigsberg et al. 2020; Frank et al. 2017). Moreover, different field-based monitoring studies have accepted the considerable environmental effects of desalination disposals on different marine organisms, like seagrass, phytoplankton, and fish habitats (Del-Pilar-Ruso et al. 2007; Roberts et al. 2010). Nevertheless, these environmental effects are typically predominant only near the location of discharge (Abdul Azis et al. 2003).

It is worth noting that the effects of increased temperature were remarkable in thermal plants, which most of them alternated using membrane-dependent desalination methods. Also, the enhancement in the disposal systems has confirmed to decrease the temperature down to 2–4 °C, rapidly in the initial dilution area at environment (Ihsanullah et al. 2021). In addition, local biodiversity might be negatively affected by the density of the reject brine. The density of reject stream from the RO desalination systems is over seawater, and it has a tendency to sink and distribute across the seafloor in shallow coastal waters. Hence, it is highly possible to influence benthic habitats negatively. In contrast, because of the higher temperature than receiving water, the concentrate from MED and MSF plants has a lesser density, and the brine is feasible to float on the surface influencing the open water species (Lattemann et al. 2010; Gude 2016). Chemicals discharged from desalination systems into the marine ecosystem might have marked temporary and long-term effects on the marine ecology. The extent of negative effects on aquatic species relies on the sensitivity of the species to special chemicals, material intrinsic toxicity, exposure time, and the volume and dosage of the disposals (Miller et al. 2015).

Cleaning-purpose agents Different cleaning agents might be released into the environment by means of concentrate disposal. Usually, harsh acidic environments are utilized for the removal of scales or metal oxides, whereas severe alkaline environments are used for membrane cleaning like the removal of silt deposits and biofilm in RO plants. Besides these agents, it might be necessary to use several oxidants and detergents. RO membranes are typically decontaminated by the application of isothiazole, formaldehyde, glutaraldehyde, hydrogen peroxide, and chlorine (Ihsanullah et al. 2021). In MED and MSF, for cleaning the surface of heat exchanger and removal of the alkaline scales warm acid, which might include anticorrosion chemicals is utilized. The cleaning agents, especially their additives, might be deleterious to the marine environment if discharged into shallow water without a proper remediation process (Gude 2016; Papapostolou et al. 2020).

Corrosion-related pollutants The concentrate discharge might include different heavy metals that arise from corrosion of different facilities of thermal desalination systems. The brine might include remarkable rates of Cu and Ni elements if unsuitable supplies are utilized for the heat exchangers (Gude 2016). Bio-aggregation of metals in shrimp and fish might have potentially negative effects on human being health (Sadiq 2002). Investigations have stated the significant quantities of metals in all MSF discharges (Alshahri 2016; Alharbi et al. 2017; Kress 2019a). For RO systems, anticorrosion stainless steel is usually used in metallic facilities; nevertheless, it is likely that the brine still includes lower concentrations of molybdenum, iron, chromium, and nickel (Gude 2016; Ihsanullah et al. 2021).

In the MED and MSF plants, the metallic facilities are constructed with titanium, aluminum brass, aluminum, carbon steel, stainless steel, and copper-nickel alloys (Gude 2016). The availability of special metals like Cu and Fe in concentrate disposal is of increasing concern if available in significant dosages. Nevertheless, limited dosages of them are regarded harmless for aquatic communities. Furthermore, the concentrate disposal may include residues of oxygen scavengers like sodium sulfite, hypochlorite ions, and hydrazine that are applied as anticorrosion chemicals (Umoren and Solomon 2020). If these agents are discharged into shallow water without a proper treatment process, they might be deleterious to the marine environment (Gude 2016).

Foaming, biofouling, scaling, and turbidity-resistant additives Antifoaming chemicals like fatty acids, fatty acid esters, polypropylene glycol, and polyethylene are usually employed in thermal desalination systems to decrease the rate of foaming. Even though these agents are supposed to be harmless, and their dosage in the brine stream is lower than the toxicity level, their limited biodegradability is still challenging and hazardous to the marine ecosystem (Kim et al. 2015; Gude 2016). Nevertheless, replacing thermal systems with membrane-based ones has considerably decreased these effects (Ihsanullah et al. 2021).

In almost all thermal desalination systems, antibiofouling additives like sodium hypochlorite and chlorine are utilized, which cause the generation of halogenated organic compounds. In the RO systems, these chemicals are typically limited to avoid presenting damage to the polyamide membrane. Nevertheless, they may available in higher dosages in comparison with receiving water, if not eliminated or neutralized, and might threaten the marine species lifecycle (Kim et al. 2015). Also, sodium bisulfite, which is commonly utilized for dechlorination, might result in intensive oxygen reduction if overdosed (Darwish et al. 2013).

Usually, antiscalants are polymeric materials that are usually utilized in the pre-treatment of feed water. Polyphosphates, sulfuric acid, polycarbonic acids, and phosphonates are common materials used for the prevention of scaling in desalination systems. Their average dosage is typically below the toxicity level, and most of them are biodegrade and hence do not present any significant hazards to fishes or other organisms (Gude 2015; Petersen et al. 2018). However, it has been stated recently that polyphosphonate antiscalants integrated with hypersaline waters have several effects on special species of reef-building corals in the Aqaba Gulf (Petersen et al. 2018). Moreover, it is conveyed that brine which includes iron-hydroxide coagulants and polyphosphonate-based antiscalants can motivate physiological and compositional variations in the microbial habitats (Belkin et al. 2017). Nevertheless, almost all of the challenges were related to conventional antiscalants, and after the application of carboxylic polymer-dependent antiscalants, their adverse effects have been removed (Hamed and Al-Otaibi 2010). Furthermore, because of severe rules determined by WHO (world health organization), numerous desalination systems have halted the addition of antiscalants (Voutchkov et al. 2019). Generally, the treatment of the brine formerly discharging into the sea and application of harmless antiscalants can remarkably decrease their adverse effects on the marine ecology (Kress et al. 2020).

To decrease the amount of turbidity and other foulants to reach a safe level in desalination systems, pre-treatment systems are frequently used. Typically, for the removal of turbidity by media filtration and coagulation, coagulants are utilized in RO systems (Ihsanullah et al. 2021). The backwash water from the environment filter, which includes coagulants and turbidity, is usually discharged into the seawater. Their availability might increase the number of suspended solids of the concentrate, result in pollutant coloring, and decrease the penetration of light, which can remarkably damage the marine ecology (Lattemann et al. 2010; Gude 2016). It is observed that in the brine stream the presence of polyphosphonate and iron-hydroxide coagulants decrease microbial and biomass generation (Belkin et al. 2017). The presence of FeH_6O_3 in the backwash water is the major reason for the conservative red color of the desalination brine stream that results from coagulant usage during the pre-treatment stage. Nevertheless, the recent emerging plants have been furnished with some equipment to remove FeH_6O_3, and as a consequence translucent brine has an appealing effect on the ecology (Voutchkov et al. 2019).

Water intake route

Feedwater for desalination of seawater is mainly supplied by either open seawater water intakes (the more practical intake source) or subsurface intakes (Kress 2019b). Several investigations stated that the application of open intakes can attitude a considerable hazard to marine organisms, which in turn can damage them. Because intake water not only contains water and salt but also is an habitant that involves a complete ecosystem of invertebrates, fishes, and phytoplanktons. Over the intake systems, some undesirable mechanisms significantly endanger the aquatic life cycle. Entrapment, impingement, and entrainment of marine entities through seawater intake are of serious environmental footprints (Sharifinia et al. 2019; Wei et al. 2020; Alvez et al. 2020; Wang and Jiang 2020). Larger aquatic organisms like fish, plankton, fish eggs, shellfish, jellyfish, algae, and crabs can be killed due to the collision impingement on the intake screen mesh. Also, another unfavorable effect related to the impingement can be discharging of chemical waste driven by different types of agents, which is utilized for clearing the screen meshes. In addition, smaller organisms like bacteria, plankton, and algae can be killed because of entering the desalination facilities or trapping in the intake process (Missimer and Maliva 2018). They are discharged back into the seawater and cause a mismatch in the ecosystem. As a result, decreasing marine organism biodiversity and reduction of feedwater flow rate can be two major adverse effects of impingement and entrainment. The unstable quality of the feed water because of the seasonal changes is another serious challenge. Moreover, the presence of significant volumes of algae might cause a transient shutdown of the desalination plant (Nagaraj et al. 2018). Besides the environmental effects, the trapping of marine organisms causes a considerable requirement for intensive pre-treatment, which in turn increases both economic costs and energy consumption (Villacorte et al. 2014; Henthorne and Boysen 2015).

Nevertheless, by the application of a subsurface intake source, the aforesaid adverse impacts of intake systems on aquatic organisms can be alleviated (Henthorne and Boysen 2015). Moreover, by the application of subsurface intake systems, not only less or even no chemical additives needed for the pre-treatment process and, in turn, offer less energy consumption but also there would be no entrainment of marine organisms (Dehwah and Missimer 2016). Nevertheless, in comparison with surface intakes systems, due to difficulty in obtaining permission, site-specific feature, and high cost, there are limited subsurface-based desalination plants (Dehwah and Missimer 2016). According to the results of the life cycle assessment (LCA) of researchers (Al-Kaabi and Mackey 2019a, b), compared with subsurface intake, surface intake had higher ecological footprints, whereas subsurface intake offers a remarkable energy decrease of around 30%. Also, the construction intake systems can heavily influence the water quality through disrupting the ocean floor, which causes the suspension of sediments, nutrients, and contaminants. Impingement and entrainment cause the loading of dead biomass and debris from the blocked screens and pipelines, which might be posed a further adverse influences on the marine ecology (Kress 2019b). Nevertheless, it is crucial to note that a few numbers of literature reported on the actual explorations of the undesirable influences of the intake structure on marine life (Voutchkov et al. 2019; Kress 2019b; Wang and Jiang 2020). To precisely assess the potential effects of the desalination intake systems, comprehensive site-specific and monitoring explorations are required.

Minor effects

During the daily process of desalination organizations, turbines, the pumps with high pressure, and energy recovery systems generate a significant rate of noise and vibration (over 90 dB(A)) (Ameen et al. 2017; Liu et al. 2018; Heihsel et al. 2019). This excessive degree of vibration and noise might have adverse effects on marine species and the residents who live in proximity (Seyfried et al. 2019). Moreover, a desalination process with a volume of 5000–10,000 m^3/d requires almost 10,000 m^2 of the area (Sadhwani et al. 2005). Nevertheless, because other plants and structures employ the land similarly, as a result, desalination plants themselves directly do not pose a remarkable effect.

Regardless of the generation of concentrate brine, desalination plants produce a massive volume of solid waste. In comparison with thermal desalination plants, RO usually produces more solid waste. The composition of solid waste greatly determines its effects. Nevertheless, it is expected to have lower negative effects if undergoes proper treatment or recycling process. The kind and volume of generated solid waste must be observed precisely and continuously, and stable treatment or discharge methods have to be used to reduce its potential negative effects on the environment (Ihsanullah et al. 2021).

Moreover, in the evaporation pond, the soil structure might weaken because of hypersalinity during brine disposal on the dry soil, since Ca^{2+} is replaced by Na^{2+} in the exchangeable ion complex (Heck et al. 2016). Also, deterioration of the visual appearance is another negative effect of the brine discharge on the evaporation pond. Considering the deep-well injection technique, it might damage the subversive soil or even leads to groundwater contamination when an subversive water aquifer is available. Lately, Nanayakkara et al. explored the ecological effects related to the brine discharge from a low-pressure RO system. According to their results, in comparison with uninfluenced soils, lower K^+ values and higher pH in the influenced soils implied exchanging available potassium ion and proton in soil with available Mg^{2+} and Ca^{2+} in brine (Nanayakkara et al. 2020).

Plant construction is usually followed by the simultaneous installation of intake and outfall equipment, construction of internal roads, pre-treatment/post-treatment facilities, and sewerage and electricity networks. They are harmful to flora, fish, mammals, bird communities, noise pollution, and dust and fumes emissions. If the construction process takes 2 years to the first operation, the aforesaid adverse effects would be considerable (Olabarria Gonzalez 2015). One major environmental effect related to the installation of plants is the construction of marine outfalls, which increase habitat extinction and turbidity. Moreover, it is advisable that future desalination plants take some measures to minimize their land footprint.

Also, the installation of new desalination systems in unpopulated areas causes human settlements since it will offer employment opportunities for the local residents and encourage migration there. However, some mitigative measures must be adopted for fishing activity otherwise it will cause unemployment of local fishermen (Arafat 2017).

If desalination is not treated effectively, it can adversely affect the final water quality and, in turn, might pose different hazards to public health. To be more specific, the intake water source can contain a significant volume of petroleum, TDS, or other microbial pollutants. The treatment process is directly responsible for the disinfection of additives and their by-products besides preventing bacterial regrowth (WHO 2007).

Potable water is an abundant source of crucial chemicals that are essential to human health like potassium, iodine, chloride, fluoride, sodium, manganese, magnesium, and calcium. In contrast, because of the natural process of eliminating different ionic pollutants and salts, desalinated water lacks most of such vital elements (WHO 2007). WHO confirms that desalination removes different crucial minerals like fluoride, magnesium, and calcium (Edition 2011). Moreover, the absence of fluoride in desalinated water is observed, which is associated with tooth decay (WHO 2007). In order to reach a favorable quality in the finished water, demineralization is developed as a post-desalination operation performed by the application of limestone dissolution filters with CO_2 or mixing finished desalination water with groundwater (WHO 2007). Regrettably, a great deal of desalination equipment does not add up all of the important minerals. As a result, more severe regulations have to be implemented to make sure that final water does not lack any essential nutrients.

The environment can have several effects on desalination per se. For example, the quality of feed water can remarkably influence the desalination systems. Seawater derived from areas with poor quality water definitely will pose further pre-treatment process before desalination, which adds extra cost and might cause ecological contamination (Kress 2019c). Low quality of water stream might include various contaminates with a substantial fouling inclination that can greatly influence the efficiency of desalination systems, especially RO (Lattemann and Höpner 2008). The intake screens and RO membranes are strongly influenced by detrimental algal blooms. Also as previously discussed, the impingement of marine species decreases or sometimes avoids the passing feed water for desalination plants. Moreover, rapid fluctuations in seawater formulation because of careless disposals in the proximity of the intake or polluted riverine runoff gravely damage desalination systems. Also, the site location for desalination equipment is a critical parameter that can markedly influence plant efficiency (Ihsanullah et al. 2021). Desalination systems located close to the main shipping route are exposed to the constant hazard of oil contamination because of oil spillage, which harmfully affects the quality of desalinated water (Elshorbagy and Elhakeem 2008). It is also important that the hydrology of the site has to be considered to prevent desalination systems from flooding.

Alleviation strategies for environmental adverse effects

Brine discharge

Several studies anticipated the possible effects of brine disposal of desalination systems on the groundwater and coastal aquifers (Nassar et al. 2007; Tularam and Ilahee 2007). For efficient brine disposal, surface water discharge is the most practiced solution (Panagopoulos et al. 2019). Diluting the stream of rejected brine with the outputs of wastewater remediation facilities before wasting to the marine ecology is regarded as one of the desirable options. Also, brine treatment is a favorable option because it leads to more freshwater recovery and decreases environmental contaminants and the reduction of waste volume (Ye et al. 2019; Panagopoulos et al. 2019). In addition, the adverse effects of brine can be decreased by the utilization of less toxic and biodegradable chemicals during the desalination process or by using systems with lowest chemical consumption. The harmful effects of brine can be decreased by improving the recyclability and reusability of materials extracted from brine. Nevertheless, in spite of the desirable findings on a small scale works, intensive research efforts require to be conducted to evaluate the possibility of brine remediation in industrial desalination systems (Panagopoulos and Haralambous 2020a; Ihsanullah et al. 2021).

The long-term effects of rejected brine on the marine ecosystem can be decreased by discharging the brine using multiport diffusers, hence removing the dependence of brine stream dilution on the operation of power plant and the capacity of cooling water. Also, without the application of cooling water for brine dilution, the difference between the concentrate temperature and received water bodies can be decreased (Petersen et al. 2018; Frank et al. 2019). Recently, Wood et al. stated that the brine dilution by cooling water of power plants can prevent the production of dense concentrates to some extent (Wood et al. 2020). As recommended, a 40-times dilution of the brine stream seems to be enough to guard 99% of the marine plants (Falkenberg and Styan 2015).

Careful studies must be performed to decrease effects like the outfall design for the highest dilution and the application of eco-friendly chemical additives. For controlling the dosage and volume of the salinity plume besides brine distribution, multiport diffuser structures can be used (Amy et al. 2017). Recently intensive research has been performed to produce innovative diffuser structures and retrofit available ones (Roberts 2015; Abessi and Roberts 2017). Moreover, the negative effects of concentrate disposal can be mitigated by decreasing its volume by MLD and ZLD methods (Cappelle et al. 2017; Panagopoulos et al. 2019; Lu et al. 2019). Nevertheless, intensive work requires to be conducted to evaluate the possibility of ZLD structures in viable applications (Semblante et al. 2018; Nayar et al. 2019). Moreover, the temperature, salinity, and chemical dosage in the concentrate disposal can be decreased using effective brine dilution strategies. Following the environmental regulations for the prevention of environmental adverse effects posed by brine discharge in the water bodies, the outfalls of desalination systems must be regulated properly to have a minimum effect. Especially, the desalination outfalls must undergo brine dilution effectively (Shrivastava and Adams 2019). In this context, far-field modeling methods like MIKE 3 and Delft 3D and near-field modeling methods like VISJET, VISUAL PLUME, and CORMIX were introduced to anticipate the mixing behavior and diffusion of disposal brine (Palomar et al. 2012; Kress 2019d). It is totally essential to install the reject stream away from fertile and environmentally sensitive regions. The reject stream can be a precious water resource, because chemicals, salts, and minerals can be extracted by treatment of the reject brine stream and decreasing its quantity (Panagopoulos and Haralambous 2020a). The major solutions and sophisticated methods for applying, handling, and controlling the reject stream for the recovery of water and metals are discussed as the following. Figure 5 summarizes frequently practiced solutions for the remediation of the reject stream (Mustafa et al. 2020; Ihsanullah et al. 2021).

Considering the brine content, the application of polyphosphonate-based antiscalants results in phosphorus disposal in the marine environment. In order to minimize their disposal, it is suggested to use sophisticated eco-friendly antiscalants, which contain biodegradable materials (Pervov et al. 2018). Concerning the heavy metals that might be detected in the reject stream because of metallic equipment corrosion mainly in thermal-dependent plants, a solution will be the application of powerful anticorrosion materials like titanium, hyper duplex stainless steel, and super duplex stainless steel (Panagopoulos and Haralambous 2020a). Nevertheless, in comparison with conventional metallic materials utilized in thermal-based plants, they are cost-prohibitive at least 1.6 times (Panagopoulos and Haralambous 2020b). It must be mentioned that for the treatment of brine in desalination systems, the application of super-resistance materials is necessary because the significant dosage of chloride is extremely dangerous (Panagopoulos 2020a). Also, to reduce the corrosion of the metallic equipment in the thermal-dependent desalination systems where metallic materials are predominantly utilized, anticorrosion chemicals are integrated into the feed water. Nonetheless, they are toxic and can cause environmental pollution (Sanni and Popoola 2019; Liang et al. 2018). In this context, the application of eco-friendly corrosion preventers that can be produced from biomass waste, natural sources, etc., is promising. Green anticorrosion materials are harmless and eco-friendly. Nevertheless, careful scientific research must be done to ascertain the efficiency of this alternative anticorrosion in desalination plants (Parthipan et al. 2018; Vasyliev and Vorobiova 2019).

Application and sequestration of CO_2

The reject stream can be applied for CO_2 application, storage, and capture (Mustafa et al. 2020), which can involve reducing the salinity of the reject stream and reduction of CO_2 emissions (Jones et al. 2019; Bang et al. 2019). Different researchers have explored the potential of capturing CO_2 from the reject stream (El-Naas et al. 2017; Kang et al. 2020; Mustafa et al. 2020). Moreover, CO_2 can convert into precious sodium bicarbonate by desalination brine (Dindi et al. 2015). The consecutive degradation of Mg and Ca in the brine improved the conversion rate of CO_2 to mineral

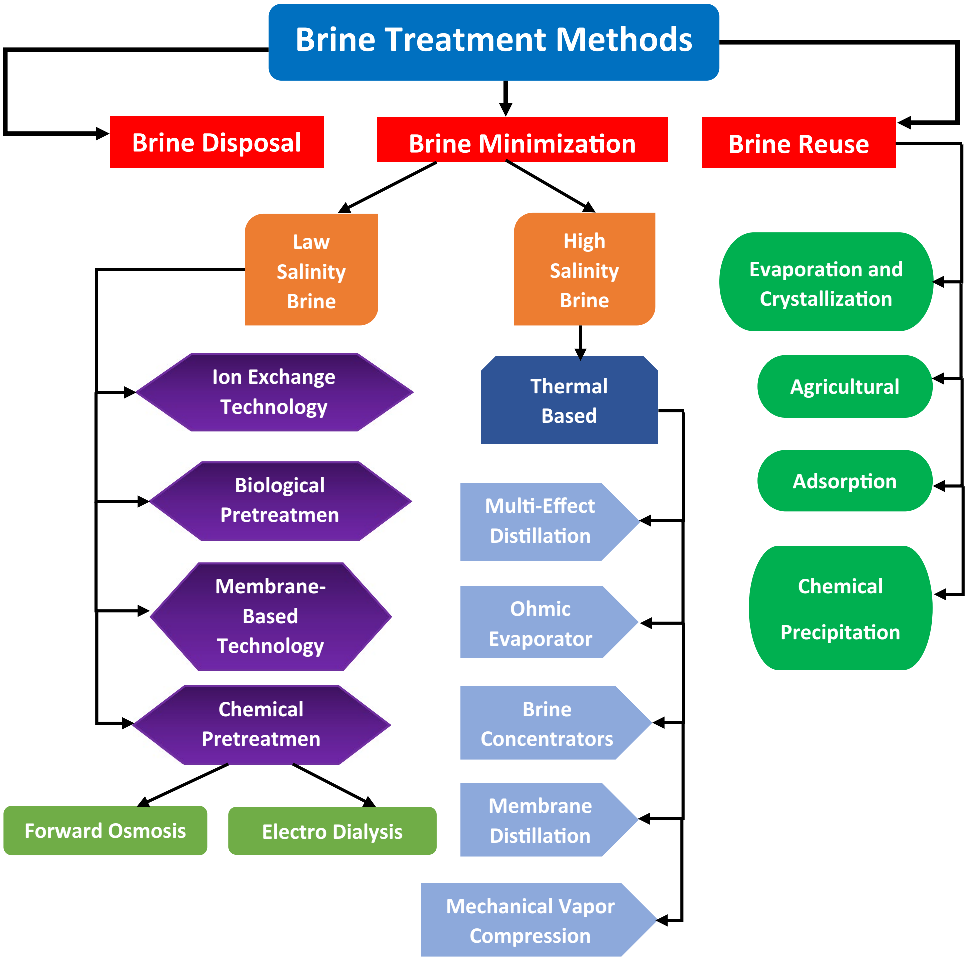


Fig. 5 Different solution for remediation of reject brine stream. Adapted from (Mustafa et al. 2020; Ihsanullah et al. 2021)

carbonates (Bang et al. 2019), whereas their simultaneous presence leads to a lower conversion rate. Mustafa et al. (2020) reported the capture of CO_2 and its application for the treatment of brine. Through a mixed metal oxide, the chloride ions were eliminated from the brine, and the final alkaline brine is converted into chloride-form hydrotalcite. The carbon dioxide was absorbed by brine and precipitated sodium bicarbonate, which removed the Na^+ from the brine and made them harmless to dispose into the ecosystem. The adsorbent could have the ability for chloride removal and CO_2 absorption in many cycles with enough reusability and recyclability (Ihsanullah et al. 2021).

Water and energy recovery

The desalination produced massive amounts of wastewater with many retained materials. Effective brine remediation can lead to water recovery from the reject stream and remarkably reduce the volume of the reject brine (Giwa et al. 2017). Figure 5 demonstrates some of the most sophisticated presents and under-development methods for the reject stream remediation and water recovery and valuable metals (Turek et al. 2017; Vane 2017; Lee et al. 2019).

Furthermore, the environmental effects can be decreased by the application of ZLD methods for treating the rejected brine. ZLD is advantageous for recovering valuable salt and fresh water from the brine and decreasing the number of reject streams. To obtain ZLD, like crystallizer and brine concentrator, different thermal- and membrane-based methods can be used, which depend on either advanced and mechanical-based methods or traditional and natural processes (Lee et al. 2019). The water and salts from the reject stream can be effectively separated using forced circulation crystallization, recycling RO, slurry precipitation, sequestration, salt solidification, wind-assisted intensified evaporation, spray dryers, evaporation ponds, and mechanical and thermal evaporation crystallizers. Because aforesaid methods are cost-prohibitive, their application is undesirable, and predicted that in the near future highly efficient ZLD methods will be accessible (Panagopoulos et al. 2019).

Because evaporation ponds rely on solar energy for evaporation of water from the concentrate disposal and depart the precipitated salts, they are most effective in semi-arid or arid regions. Also, it is cheap, simple, and highly practiced in industrial wastewater treatment processes. Nevertheless, high-cost and contamination of groundwater and habitat because of the seepage and aggregation of the micropollutants are the major downsides of this method. As a result, utilizing liners and disposal of the residual into landfills alongside stringent ecological regulations is compulsory to avoid its environmental effect. To improve the rate of evaporation and decrease the needed land for further discharge, the evaporation intensified by wind utilizes wind besides solar energy. Its process relies on natural energy sources, and compared with the traditional evaporation ponds, the requirement for land is lower (Ihsanullah et al. 2021).

The forced circulation crystallization structure relies on a mechanical operation that utilizes heat for the separation of the solid and transformation of the vapors to a purified distillate with higher than 95% water extraction. The major benefits related to the forced circulation crystallization are water generation with high quality and a small footprint when applied for waste stream application. Nevertheless, this method is complicated and needs regular cleaning. Therefore, in comparison with most of the other methods, it has a significant capital cost (Morillo et al. 2014).

Besides water recovery, a reject stream can be applied to generate energy simultaneously (Lee et al. 2019; Kingsbury et al. 2017). Because the reject stream has significant osmotic pressure because of significant salinity, mixing it with freshwater brine can be utilized as a foundation in energy of salinity gradient. The salinity gradient energy can be recovered from brine in wastewater, and theoretical estimations recommended that enough energy is recoverable. By the development of proper structures, the recovered energy can be transformed to mechanical or electrical energy. Similarly, electrodialysis reversal (EDR) and pressure retarded osmosis (PRO) can be utilized for energy recovery from the reject brine (Lee et al. 2019; Kingsbury et al. 2017).

It must be noted that although by application of RES the GHG emissions are markedly decreased, energy consumption will not decrease since it relies remarkably on the nature of each method. One way to deal with this challenge will be the application of co-generation, which simultaneously uses both thermal and electrical energy and considerably increases the performance of plant energy generation (Altmann et al. 2019). Moreover, some desalination systems are self-sufficient and employ extra energy from one cycle stage to lower pressure or increase the temperature at another stage, like MED and MSF plants. It is advisable that each desalination system utilizes effective energy consumption designs for saving energy and decreasing consumption as much as possible (Panagopoulos and Haralambous 2020a).

Brine mining

Seawater includes most of the precious elements which they are presented in the reject stream as a side-product of the seawater desalination systems. Hence, significant focus has been devoted to the mining of the precious elements from the concentrate (Ihsanullah et al. 2021). The notion of valuable materials extraction from the reject stream was suggested by Mero (Mero 1965) as it has confirmed significant breakthroughs in the treatment and reject brine reusability. Gradually people have investigated the extraction of valuable metals extraction from seawater like lithium, rubidium, cesium, sodium chloride, potassium, bromine, uranium, gold, and magnesium (Mohammad et al. 2019; Mavukkandy et al. 2019; Palagonia et al. 2020). Moreover, other chemicals and minerals like pure salts, $CaCl_2$, $CaSO_4$, Na_2SO_4, HCl, KCl, $CaCO_3$, MgO, H_2, Cl_2, and NaOH can be extracted from the reject stream utilizing different systems (Du et al. 2018; Dong et al. 2018; Randall and Nathoo 2018). At least two desalination technologies are incorporated using an MLD/ZLD scheme for the generation of solid salt, decreasing the brine quantity and recovering higher quantities of freshwater (Liu et al. 2016; Panagopoulos et al. 2019; Panagopoulos and Haralambous 2020b). For instance, Liu et al. proposed integrated electrodialysis (ED) and nanofiltration (NF) processes to reject brine streams (Liu et al. 2016). With the application of different technologies in hybrid designs for brine recovery, various high-purity solid salts can be mined rather than a single mixed solid salt. These solid salts involve $CaCl_2$, $MgCl_2$, NaCl, and the like (Panagopoulos 2020b; Panagopoulos et al. 2019). The solid salts and freshwater recovery can render the desalination process more sustainable from an economic standpoint because of presenting further profit. However, brine mining and treatment are desalination processes at significant rates of salinity and, as a result, present disadvantages like GHGs emissions and extreme energy consumption.

Moreover, valuable materials' recovery from the reject stream not only decreases the operating cost of desalination but also reduces its environmental negative effects. Also, it can increase the rate of desalination profitability under the condition that these elements could be marketed. However, the extraction process relies on different parameters like feasibility, technical maturity of the applied technology, energy evaluation, and economy (Shahmansouri et al. 2015). Regardless of extensive investigations that reported the effective mining different materials from rejected brine, the overall process at present is not economically feasible, which is one of the major barriers to commercializing these technologies (Ihsanullah et al. 2021).

Moreover, one research work explores potential utilizations of brine disposal from the desalination systems in fish farming for fishes that are adaptable to saline waters, spirulina cultivation, crops, and forage shrub irrigation (Sánchez et al. 2015). Despite the fact that this is an appealing solution, still, intensive research is required in this area to ascertain the appropriateness of the reject brine for particular utilizations and the crucial pre-treatment process (Hacıfazlıoğlu et al. 2019).

Energy usage

Excessive energy usage is the major determinant of cost for seawater desalination; hence, it is the main incentive for enhancement along with technological breakthroughs. Required energy of desalination can be significantly decreased by process enhancement, RES-based desalination, and the application of novel methods for energy recovery (Wei et al. 2017; Suwaileh et al. 2019). RES-based desalination simultaneously minimizes overall costs associated with desalination and environmental negative effects (Shokri and Sanavi Fard 2022). Moreover, the detrimental effects because of intensified energy usage can be countervailed by reducing the application of fossil fuel-driven sources and rendering the operation more effective from an energy standpoint (Lior 2017; Azhar et al. 2017; Tarpani et al. 2019; Al-Othman et al. 2019).

Careful selection of plant location

Different critical parameters must be regarded before the selection of a site for desalination systems and related works. The plant location has to be evaluated with respect to the environment, and close attention has to be dedicated to the prevention of endangering productivity and biodiversity of rare species. The plant location has to be in proximity to sea and water distribution networks, to remarkably decrease the reliance on the pipeline and pumping besides land usage for the water distribution structures. With this approach, the risk of polluting the groundwater aquifer due to pipe leakages will be prevented. The selected location should have adequate capacity for dispersion and dilution of reject hypersaline stream and degradation of any remaining chemicals (Ihsanullah et al. 2021). Also, the oceanographic conditions of the plant location should be taken into account since they will ascertain the residence time of contaminants and in turn the exposure time of marine species to these pollutants. The site must not negatively influence shipping, nature conservation, and commercial and recreational facilities (Lattemann and Höpner 2008). It is highly recommended that the desalination plants are established far away from coastal areas and residential. Some mitigative measures would be (1) people's awareness concerning job opportunities and easier accessibility to freshwater. (2) Recognizing proper site for plant construction and minimizing its effects on outdoor activities and the economy. (3) Using areas where energy and water facility lines are currently available like hydropower ports and thermoelectric. (4) Reducing the number and length of water lines and electricity (Panagopoulos and Haralambous 2020a).

Source water intake

The environmental effects associated with open intakes, like entrainment and impingement, can be alleviated to some extent by the integration of screens with multi-variant mesh sizes and utilizing low intake velocity (Shahabi et al. 2015). In order to decrease intake velocities, they should possess larger openings and be covered by mesh to prevent impingement. According to the investigations, the application of beach well intake decreases the ecological effect by 31% (Shahabi et al. 2015; Elsaid et al. 2020a). By construction of the beach well intakes and infiltration galleries under the seabed, the feasible effects of the intake system can be solved. In order to decrease or even prevent the entrainment of small species, the intake systems can be located in deeper water, offshore or underground. In power plants, the application of the cooling water in desalination as feed water can be another feasible solution to prevent the environmental effects associated with water intake (Sadeghi et al. 2020). In this way, the negative effects of entrainment and impingement besides harmful effects associated with chemical usage, construction, and land use will decrease. The intake system should be located far away from areas with scarce species, marine-threaten areas and bio-productive species. In other words, it must be located in areas that do not pose any considerable effects on the ecology of habitats. Also, improving desalination recovery will cause decreasing the feed water volume and, as a result, reduce the unfavorable effects associated with entrainment and impingement (Ihsanullah et al. 2021). Moreover, the effects can be decreased by the application of a velocity cap to alter the water flow pattern to the prevention of microorganisms entrance into the screens, bypass systems to avoid and return back the marine species to the sea, and installing net-like barriers to avoid the flow of organisms (Kress 2019b). By utilizing stable sealing methods for the aquifer and pipes, the effect of the intake arrangement on the aquifers can be decreased (Kress 2019b). The effects on benthic habitats might be diminished by prevention of erosion using typical laying pipelines and maintenance in covered trenches. In order to mitigate incidental entrapment of marine organisms, facilities must be provided by decreasing speeds ideally less than 0.2 m/s. Also, physical hurdles can effective tool to avoid entering marine species into the intake area (Kress 2019d; Kress et al. 2020).

For alleviation and controlling the environmental adverse effects related to the intake and outfall, their proper selection and design are of prime concern (Elsaid et al. 2020c).

Because of significant feasible volumetric flowrate and simple installation, open intake systems are more desirable and are the only practical solution for large-scale desalination systems. However, they have considerable environmental negative effects on the local marine ecology (Missimer et al. 2013). Although subsurface intakes present numerous ecological advantages and reduced feedwater pretreatment, intake capacity limitation is the only major disadvantage. For SWRO, the quality of Red Sea feedwater has been evaluated by Dehwah et al., and the quality with subsurface intake is considerably favorable with complete organic biopolymers and algae that removed 84% of bacteria and a remarkable decrease in clear exopolymer particles was observed (Dehwah et al. 2015). As a result, the pretreatment process and biofouling are avoided, decreasing desalination cost and energy, rendering subsurface an eco-friendly solution for SWRO desalination systems (Dehwah and Missimer 2017; Missimer and Maliva 2018). Moreover, according to the results of the life-cycle assessment of Al-Kaabi and Mackey, the subsurface intake needs 30% lower energy which causes 6% plant-wide energy saving equal to a yearly decrease in global warming potential of around 58 kton CO2-eq (Al-Kaabi and Mackey 2019b).

One of the remarkable impacts on the local marine media at the discharge area is associated with the outfalls of brine discharge from desalination systems (Elsaid et al. 2020c). Hydrodynamic modeling of brine disposal from various outfall designs plays a critical role concerning environmental effects, because it anticipates the mixing and diffusion behavior of disposed brine and hence aids to achieve the pattern of temperature, salinity, and dosage of various pollutants near the discharge point utilizing either far-field or near-field modeling methods (Malcangio and Petrillo 2010). Based on the outcomes of these hydrodynamic modeling, suggestions considering outfall form and design, besides operation restrictions in terms of temperature and salinity of brine, can be realized (Maalouf et al. 2014).

Environmental impact assessment (EIA)

To precisely assess the effects of desalination and conduct proper solutions for the reduction or removal of those effects, an environmental impact assessment (EIA) is absolutely crucial. Highlighting brine disposal numerous methods can be traced to simultaneously enhance the desalination systems and minimize its adverse environmental effects (Elsaid et al. 2020c). EIA presents a series of explorations and controlling processes to evaluate the proper area for installation of desalination equipment and some precautionary and treatment strategies for mitigation of environmental influences on coastal areas and marine ecology (Sola et al. 2019b; Sadhwani Alonso and Melián-Martel 2018). Environmental monitoring designs are expanded along the EIA to ensure the adequate efficiency of precautionary and treatment methods to protect the marine ecosystem from the negative impacts of brine disposal and implement highly protective measures when any possible ecological damage is detected (Sola et al. 2019a, b, 2020).

EIA must be conducted at the initial stages of project design because it can greatly assist in deciding on project schedule, location, execution, and many other critical factors. According to the results of the EIA report, the effects are carefully assessed, and then, a precise decision can be obtained for the project, either by accepting the project if the related environmental effects are admissible considering the policymakers regulations or to reassess with proposed suggestions to alleviate and manage the related environmental effects, or even to be rejected if they are highly stringent (Elsaid et al. 2020c). The EIA will recognize, outline, and evaluate unsuitable methods according to each separate case and the direct and indirect impacts of a project on the subsequent parameters: (a) climate, air, water, soil, (b) flora and fauna and human beings, (c) the interaction between parameters noted in the first and second cases, and (d) cultural heritage and material properties (Elsaid et al. 2020c). The procedure for EIA regarding seawater desalination systems is presented in Fig. 6 (Lattemann and Höpner 2008).

Other strategies

The effect of brine pollution on aquifer can be to some extent decreased by the application of suitable sealing methods for the aquifer and pipes (Sadhwani et al. 2005). The potential negative environmental effects of plastic bottles due to the increasing demand for drinkable water can be mitigated by the application of biodegradable and eco-friendly materials for the fabrication of water bottles and bottle recycling processes (Ihsanullah et al. 2021). Moreover, the installation of antielectrocution and collision-resistant devices on overhead power lines can be a vigorous pursuit to decrease or even prevent the negative environmental effects of desalination plants (Fuentes-Bargues 2014).

The environment intrinsically might have several adverse effects on desalination plants, which can be markedly decreased by a selection of a suitable location that provides sustainable water quality. Intake water sources close to the shore have to be prevented, and it is strongly suggested to utilize intake presented in underground or deep water layers (Dehwah and Missimer 2016).

Eco-friendly desalination technologies

The environment and desalination can be integrated for the protection of natural water sources, with suitable regulations and management strategies. The application of innovative

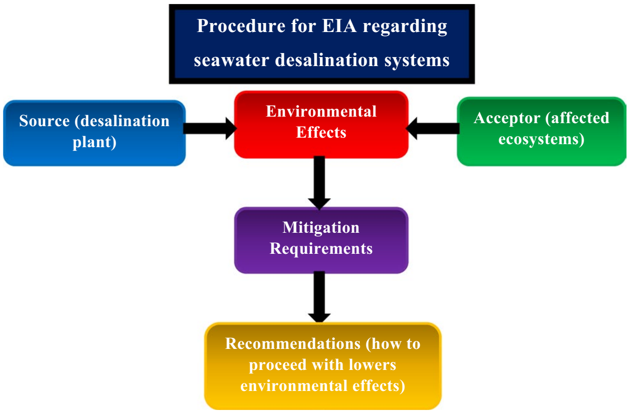


Fig. 6 The procedure for EIA regarding seawater desalination systems. Based on Lattemann and Höpner (2008)

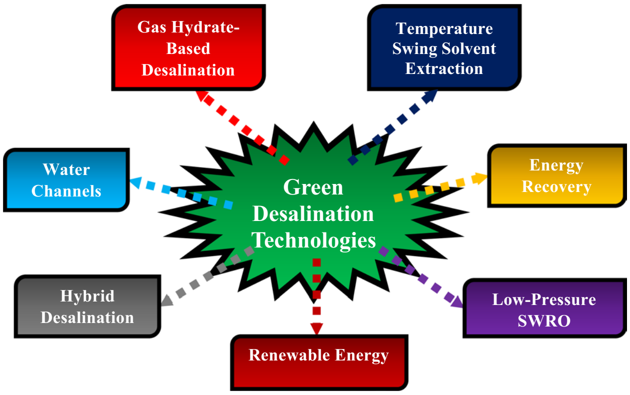


Fig. 7 Eco-friendly desalination technologies. Adapted from Ihsanullah et al. (2021)

eco-friendly desalination technologies is a highly promising notion that can mitigate the adverse environmental effects of desalination and protects natural sources as much as possible (Ihsanullah et al. 2021). Figure 7 presents various environmentally friendly technologies for the operation of desalination (Ihsanullah et al. 2021).

Renewable energy and hybrid desalination

The application of RES is another viable option to decrease the undesirable footprints of desalination on the environment (Chandrasekharam et al. 2019; Panagopoulos et al. 2019; Kang et al. 2020; Wang and Jiang 2020; Tong et al. 2020). It can be transformed into another form like electricity before application in technologies like photovoltaic-enabled RO systems or used directly in the desalination like solar still. The integrated photovoltaic and RO systems were reported to have the minimum environmental effects (Jijakli et al. 2012). The significant reason for the utilization of RES for desalination is its green and sustainable nature. Nevertheless, almost all of them are not mature enough, and intensive research has to be implemented for commercializing them (Shokri and Sanavi Fard 2022). Moreover, influent dilution to the RO systems by wastewater streams discharged by the desalination system causes a remarkable decrease in energy usage rate (Wei et al. 2020). Due to the shortcoming of each RES, their hybridization presents a sustainable option for minimizing the environmental adverse effects of conventional desalination technologies (Lee et al. 2019; Lu et al. 2019; Ang et al. 2020; Ghaebi and Ahmadi 2020). The application of pollution-free energies to operating the integrated desalination processes with ZLD has been investigated by different researchers. According to the studies of Lu et al. Membrane distillation (MD) crystallization and hybrid freeze, desalination technologies can be used for ZLD desalination with the assistance of solar energy (Lu et al. 2019; Ihsanullah et al. 2021). In addition, MD is a highly promising technology for practical application in the near future (Yuan et al. 2020; Naidu et al. 2020; Yao et al. 2020). MD that uses moderate waste heat has garnered significant focus as an energy-effective solution for desalination (Yuan et al. 2020).

To increase energy recovery and hence decrease brine disposal, energy demand, and associated costs, hybrid desalination attracts much attention. Integration of NF-RO has caused increased SWRO to permeate flow to 48% recovery and 4.8 l/min in comparison with 16.7% and 1 l/min for NF-SWRO and separate SWRO, respectively, at 40 bars. Also, at 70 bar the recovery enhanced from 48 to 80% (Al-Sofi et al. 2000; Elsaid et al. 2020c). This efficiency enhancement was primarily ascribed to a) decreasing impacts of concentration polarization in SWRO, decreasing feedwater salinity, and c) decreasing or removing scaling and fouling of SWRO membrane (Kaya et al. 2015). The combination of FO causes water recoveries from brine varying from 30 to 75% for SWRO, whereas rising up to 90% for BWRO (Choi et al. 2009). In the same way, the NF-FO-BWRO tri-hybrid obtained over 90% recovery (Altaee and Hilal 2015). Integrated MSF-MED has been detected with 21% and 32% lesser cost and 16% and 58% lower pumping energy demands in comparison with individual MED and MSF, respectively (Mezher et al. 2011). In comparison with individual SWRO, hybridized MSF/RO process had a 25% lower specific electrical energy consumption than SWRO (El-Sayed et al. 2000). Hybridized RO/MSF system has demonstrated a cost decrease of 17–24% in comparison with individual MSF by utilizing SWRO brine as a recycle stream in the MSF system (Helal et al. 2004a, b). An NF-SWRO-MSF tri-hybrid system was explored at the pilot scale and has demonstrated a raised MSF top brine to 160 °C, hence augmenting distillate and permeate recovery (Hamed et al. 2009).

Energy recovery and gas-hydrate-based desalination

By recovering energy losses from desalination plants and waste energy, required energy can be effectively optimized (Tan et al. 2020; Morciano et al. 2020; Lawal et al. 2020). Lately, researchers have suggested different energy recovery methods that present different benefits from an economic and ecological standpoint (Morciano et al. 2020). Because the energy recovery systems considerably increase effective energy exploitation and decrease the carbon footprint when fossil-fuel-driven energy sources was used, recently thermal desalination technologies utilizing waste heat have garnered ever-increasing attention. Especially, low-grade heat recovered from industrial operations or from geothermal energy sources demonstrates a precious source for the conduction of desalination systems (Wang et al. 2011; Bundschuh et al. 2015). In this context, the application of small-scale desalination facilities for freshwater production operated by waste heat from electric power generators was experimentally explored by Morciano et al. (2020). The water purification technology depends on passive, multi-stage, and thermally enabled MD equipment. The distiller is operated by low-grade waste heat with a temperature less than 80 °C, recovered from the coolant or exhaust gas circuit of small diesel engines for electricity generation. According to the results of the experiment, up to 1.12 kWm^{-2} can be recovered in regular operating situations, which present almost 2.61 $Lm^{-2}\ h^{-1}$ freshwater productions from seawater. With the assumption of a two years life-time and constant full load operating situations, the price of the produced fresh water is projected to be approximately 6 $\$/m^{-3}$, which is on a par with that of other small-scale and traditional desalination systems. Moreover, this productivity can be improved by modifying the number of distillation stages. These results might provide simple, cheap, effective, and sustainable tools for freshwater production from recovered waste heat. In other words, the critical features of this solution rely on the following three concepts: (1) cost-effective, because of the application of frequently available and cost materials, (2) robustness, because of the totally passive design, which does not need any mechanical moving part and (3) sustainability, due to the recovery of thermal energy which otherwise will be loosed to the ambient. Hence, this solution is beneficial from a fuel economy perspective. Hence, this solution can be significantly efficient for desalination and supplying fresh water for remote and off-grid areas, particularly in urgent conditions. Moreover, the authors stated that in the near future, the discussed system might be directly incorporated into the coolant circuit of the power generators at the design stage (Morciano et al. 2020).

Efficient controlling strategies of waste thermal energy are regarded as one of the essential challenges in different industries, which are classified into low- and high-grade waste heat streams. Low-grade waste heat resources are not economically practical to recover and are back to the ambient, whereas high grade is usually recovered by the plant processes (Ammar et al. 2012a). One solution to use the low-grade heat resources of a process plant is the production of drinkable water for human applications (Wang et al. 2011; Ammar et al. 2012b). Moreover, low-grade RES like geothermal with a wellhead temperature lower than 100 °C can be used to operate desalination systems (Barbier 2002; El-nashar 2010). One of the major benefits of a low-grade energy stream is associated with GHG emissions. Apparently, the conduction of desalination plants with fossil fuel sources heavily contributes to the global warming issue. However, low-grade energy resources like geothermal energy and waste heat from process plants produce the lowest GHGs (Rahimi et al. 2014). In this context, Rahimi et al. (2014) study a new MED system operated by the low-grade heat source, which is maximally exploited using a multistage flashing process, to improve freshwater production. Results show that in comparison with optimized traditional MED systems, the efficiency enhancement concerning freshwater production is up to almost 50% better, with a little increase in the pumping energy consumption and a 4% to 6% reduction in the specific capital cost (Rahimi et al. 2014).

Also, gas hydrate-based desalination has been an attention-grabbing alternative technology (Zheng and Yang 2020; Babu et al. 2020). Recently, for conduction and decreasing the energy costs of gas hydrate-based desalination systems, the low application of cold energy from LNG gains considerable focuses from researchers. Based on the outcomes of process simulation and economic assessment of hydrate-driven desalination by using cold energy from LNG, the levelized cost of water is only around 1.11$m^3/\$$ (He et al. 2018; Chong et al. 2019). Hence, the commercialization of gas hydrate-based desalination technologies is projected to be highly feasible in the imminent future. Also, due to the environmentally friendly nature of gas hydrate-dependent desalination systems, this technology was considerably attention-grabbing in recent years. Recently, Zheng and Yang (Zheng and Yang 2020) introduced an innovative multifunctional desalination system using gas hydrate with different operating conditions and separation techniques. By the application of simulated seawater, the desalination properties under various separation conditions were implemented and for the desalination of a natural seawater sample, the hydrate-purging system with a desalination performance of over 80% was selected. According to the experimental findings, the elimination performances of various ions in the seawater were analogous, and their variance was associated with the asset of ionic hydration. Moreover, they designed and implemented a constant desalination system comprising washing and purging, separation, and multiple injection operations. The final desalination performance utilizing hydrate-purging technology was higher than 80%, and the freshwater recovery was over 30%. Overall, these results can be significantly crucial to developing gas hydrate-dependent desalination systems (Zheng and Yang 2020).

Low-pressure SWRO and functional water channels

The incessant enhancement in SWRO (seawater reverse osmosis) technologies has decreased the extent of energy-reliance of desalination plants. Compared with the conventional desalination processes, a low-pressure SWRO membrane required a minor energy (Al-Najar et al. 2020; Al-Karaghouli and Kazmerski 2013; Kurihara and Ito 2020; Ihsanullah et al. 2021). The membranes of RO can be adjusted to enhance the membrane properties to present minimal environmental harmful effects (Kurihara and Takeuchi 2018; Matin et al. 2019; Al-Najar et al. 2020). By integrating a low-pressure SWRO membrane, a two-stage with low-pressure and high recovery SWRO system a 20% decrease in energy was probable. Similarly, 30% energy saving was feasible through the SWRO-PRO-integrated process (Kurihara and Sasaki 2017; Kurihara and Takeuchi 2018). Das et al. (2019) have reported the application of a cost-effective and green method of bio-inspired innovative membranes and MD. Moreover, membrane crystallization as an MD-dependent idea that uses hydrophobic microporous membranes has been broadly explored as an energy-efficient method in salt extraction and desalination from the reject stream (Sparenberg et al. 2020; Quist-Jensen et al. 2016). Current improvements in low-energy FO imply that such membranes can play a pivotal function in the future of pollution-free SWRO (Aziz et al. 2020; Qasim et al. 2020; Im et al. 2020; Lee et al. 2020). The environmental effects of applied chemicals in desalination can be alleviated utilizing harmless chemicals (Wang et al. 2019; Pervov et al. 2017).

Critical breakthroughs in RO desalination systems, like the design of polyamide TFC membranes and energy-recovery equipment, have caused considerable benefits concerning energy performance and productivity (Lee et al. 2011). However, still, some challenges in water remediation technologies must be overcome. Inadequate rejection of boron ions and herbicides, pesticides, hormones, and other micro-contaminants by polyamide TFC membranes, propel commercial water facilities to utilize cost-prohibitive pre-treatment and post-treatment stages (Werber et al. 2016). These issues present intrinsic material restrictions known as the solution-diffusion mechanism that controls transportation in these membranes and causes robust permeability-selectivity trade-offs for ions and inadequate rejection of uncharged micro-contaminants (Park et al. 2008).

An innovative form of membrane structure like natural water channels (aquaporins) is required to bypass these challenges. Due to their hydrophobic inner channels squeezing water into a single file design that generates a considerable transportation rate of water, these protein membranes possess significant water permeability and excellent selectivity (Noy and Wanunu 2019). They have been integrated into polymer or lipid membrane matrices to produce strong and scalable biomimetic membranes (Tang et al. 2013); however, this solution is challenging due to the trade-offs related to stability and the price of protein. Hence, aquaporins in these membranes have been replaced with their synthetic analogs like G-quadruplexes or imidazole-quartets (Le Duc et al. 2011), which produce certain water channels that create similar 1D water wires. In this context, Song et al. (Song et al. 2020) develop an innovative form of artificial water channel, namely peptide-appended hybrid[4] arene (PAH[4]), which gathers into the lipid membrane, and in contrast to other artificial water channels, it provides a tortuous path for H_2O molecules to follow. Figure 8 presents a cross-sectional molecular dynamics simulation snapshot of the permeation of water by a PAH [4] bunch entrenched in a lipid bilayer patch, with multiple water wires (Song et al. 2020). It produced highly powerful monovalent ion rejection, with the stated permeability and the selectivity of water to salt around 4 times higher than that of modern TFC membranes. Hence, Song et al. predict that with adequate packing of PAH [4] channels into the membrane, the permeability-selectivity trade-off of the polyamide RO membranes will be broken. This concept is truly fascinating because, if they are manufactured at a large scale, not only their overall capital and energy costs will decrease but also the quality of commercial desalination systems will be greatly enhanced. Nevertheless, for this purpose still, there is a long way ahead and some challenges must be surpassed. Significant PAH [4] loadings, which are predicted to limit the channel dynamics in the membrane, can possibly decrease the performance of blocking of ion. Currently, the PAH [4] membrane cannot suffer the pressures needed for RO desalination systems. Hence, by putting it on support and proving that the final sandwich structure is strong and scalable enough, viable applications will be feasible. This support surface can potentially limit the unit capability of PAH[4] to produce water channels (Noy and Wanunu 2019). Determining the performance of the micro-contaminants rejection in these channels still requires intensive research work. In conclusion, membranes relying on water transportation by transient channels demonstrate a promising future to realize high selectivity and permeability in the water desalination field (Noy and Wanunu 2019; Lim et al. 2020; Song et al. 2020).

The pass way to the industrialization of membranes equipped with functional channels for potable water is simultaneously challenging and promising. Increasing selectivity on the ionic species and a considerable decrease in membrane production cost will be occurred by the application of

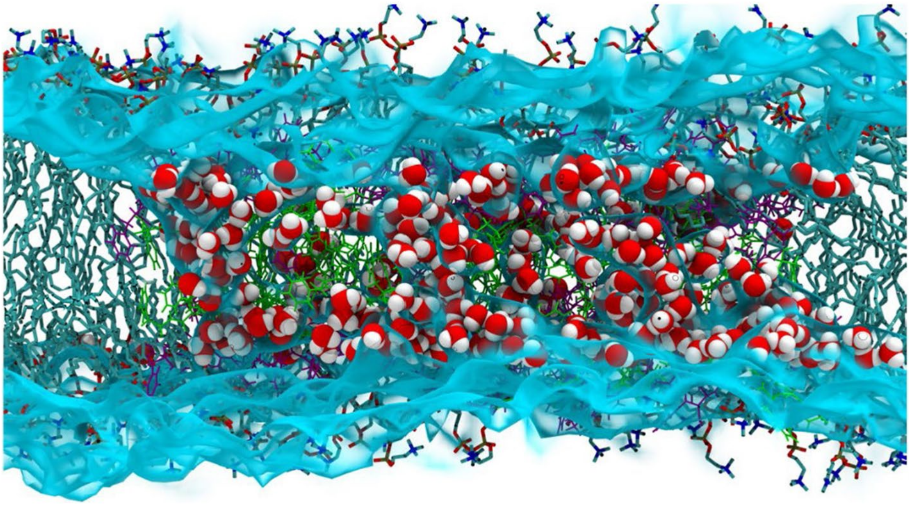


Fig. 8 Cross-sectional molecular dynamics simulation snapshot of water permeation by a PAH[4] cluster entrenched in a lipid bilayer patch, with multiple water wires. Adapted from Song et al. (2020)

functional motifs, embedded in appropriate support (Gonzalez-Perez et al. 2018). Definitely, this novel technology will be of great advantage for potable water production utilities because of its increasing performance and decreasing costs. Some of the noticeable challenges are discussed hereunder.

Membranes cost, especially for potable water production, is a disconcerting challenge. Cellulose, polyamide, and polysulfone/polyethersulfone are the major polymer-based materials that are used to fabricate current membranes. Future membranes have to be cost-competitive and possess a considerable flux/productivity rate. Nevertheless, to benefit from the higher fluxes presented by the functional channels, innovative module concepts are needed to accelerate enough turbulence to decrease the impacts of concentration polarization from an effective energy standpoint. Indeed, for using its potential, an appropriate module is necessary for a high flux membrane. Moreover, it must be mentioned that high flux does not remove the influence of the osmotic pressure needed to purify water from salt (Gonzalez-Perez et al. 2018).

Another critical problem is the mass production of membranes and their scalability. For instance, the production of a 50 cm^2 membrane may be adequate for a good experiment; however, on an industrial scale, thousands to millions of cubic meters of membranes require to be produced regularly (Livingston and Baker 2017). As a result, the scalability of the membrane production concept is highly crucial. Moreover, according to the type of application, the life cycle of present polymeric membranes is usually 1–5 years. Hence, for the development of new membranes, the conduction of long-term stability testing is critical. In order to avoid loss of functionality and leaching of membrane material during the life cycle, the membrane should be inert (Gonzalez-Perez et al. 2018).

During the lifetime of the membranes, retention of solutes has to be maintained at a high and stable level. A decrease in retention is harmful to membrane efficiency and remarkably decreases process reliability. To accelerate applications of functional channel membranes, their reliability in pilot and industrial scale applications must be proved. Then, essential life-cycle costs, and the same approaches for comparing the efficiency of various functional channel membranes with standard membrane systems, can be determined. For the applications of functional channel membranes in the market, careful techno-economic studies are crucial (Gonzalez-Perez et al. 2018).

Temperature swing solvent extraction (TSSE)

Application of solvent extraction as an effective, simple and cheap separation method in different processes of chemical engineering is inevitable. Due to the fact that solvent extraction is not dependent on evaporative phase-change and is membrane-less technology, it is fundamentally different from common traditional water desalination technologies. Hence, the solvent extraction method potentially can be considered as a competitive alternative water desalination technology that can be transformational in the water industry. This method can replace the common cost-prohibitive desalination methods in dealing with hypersaline brines which RO cannot overcome (Boo et al. 2019). Moreover, although the membrane-dependent RO systems is confined by the hydraulic pressure, temperature swing solvent extraction (TSSE) is not limited by the degree of feedwater salinity level. Since TSSE desalination does not need water phase changing, the energy-intensive vaporization enthalpy is effectively overcome and remarkably higher energy performance can be obtained, especially for ultrahigh salinity brines (Bajpayee et al. 2011; Boo et al. 2019). This will fundamentally enhance the sustainability of domestic desalination systems, water treatment processes, and landfill leachate. To be more specific, the mechanism of the TSSE

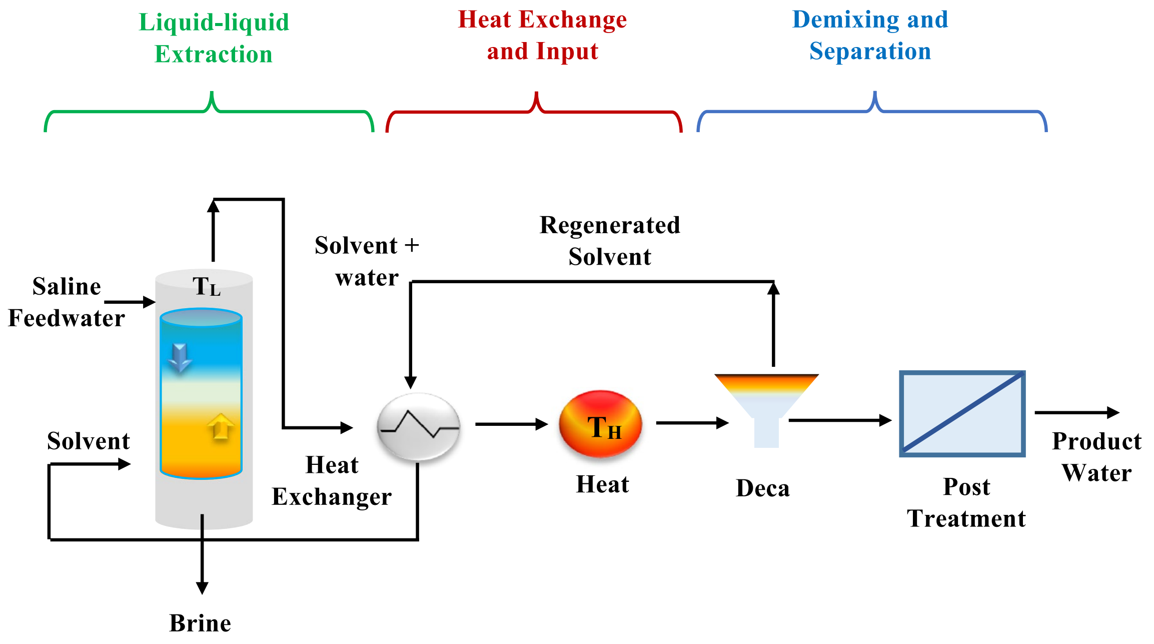


Fig. 9 PFD of a constant TSSE desalination method. Reproduced from (Boo et al. 2019)

method is that at room temperature addition of a solvent with different levels of water solubility based on temperature helps the solvent extract only water, not salt molecules. Then, the mixture of solvent and extracted water is taken out and heated. The heating of the solution results in the separation of water and solvent. Finally, by this method, purified water that is salt-free is produced. Process Flow Diagram (PFD) of a constant TSSE desalination method was presented in Fig. 9 (Boo et al. 2019).

For evaluating the performance of the TSSE, Boo et al. (Boo et al. 2019) conducted an experiment with three amine solvents including N, N-dimethyl cyclohexylamine (DMCHA), N-ethylcyclohexylamine (ECHA), and diisopropylamine (DIPA). According to their investigations, this method was demonstrated to eliminate up to 98.4% of salt from hypersaline brines with salinities as high as around 234,000 ppm TDS. DMCHA and ECHA generated water with the minimum solvent residues and salt content, while DIPA presents maximum water extraction performance. Moreover, not only during the process high water recovery of around 50% was obtained but also in the case of hypersaline brines osmotic pressure considerably decreased.

Challenges and future perspective

The environmental effects of desalination and energy consumption are highly controversial issues. Different disconcerting challenges greatly impede the alleviation of negative effects associated with desalination. For instance, the ever-growing requirement for freshwater has caused neglecting environmental regular monitoring and EIA studies frequently. The data associated with the systematic monitoring of desalination systems are typically unpublished. Moreover, the dearth of enough information revealing the real long-term environmental impact of desalination under real-world conditions renders the evaluation process extremely problematic. Field-dependent monitoring of the environmental effects of the desalination systems is barely presented in the literature. Moreover, full-scale laboratory experiments are absolutely crucial to the anticipated effects of desalination presented in the various literature. The climatic situations in different locations of the world may change these effects and even result in several synergistic effects (Ihsanullah et al. 2021). In order to reach well-defined aspects of impacts that are driven by desalination discharges, identification of aforesaid effects is inevitable. In addition, before constructing new desalination plants, close attention to the environmental conditions of the site is critical.

Future desalination regulations have to be inextricably associated with the full-scale assessment by LCA and EIA tools. Application of these methods during all stages of desalination including cleaning, pre-treatment, outfalls, and source intake water can be directed toward sustainable desalination. Similarly, advanced submerged or subsurface intake source and dilution of reject brine using improved mixing at the disposal areas can offer a roadmap to reach a significant breakthrough concerning green desalination. Moreover, the effects of innovative methods may be

Fig. 10 Summary of mitigation measures for minimizing environmental footprints of desalination. Based on Elsaid et al. (2020c)

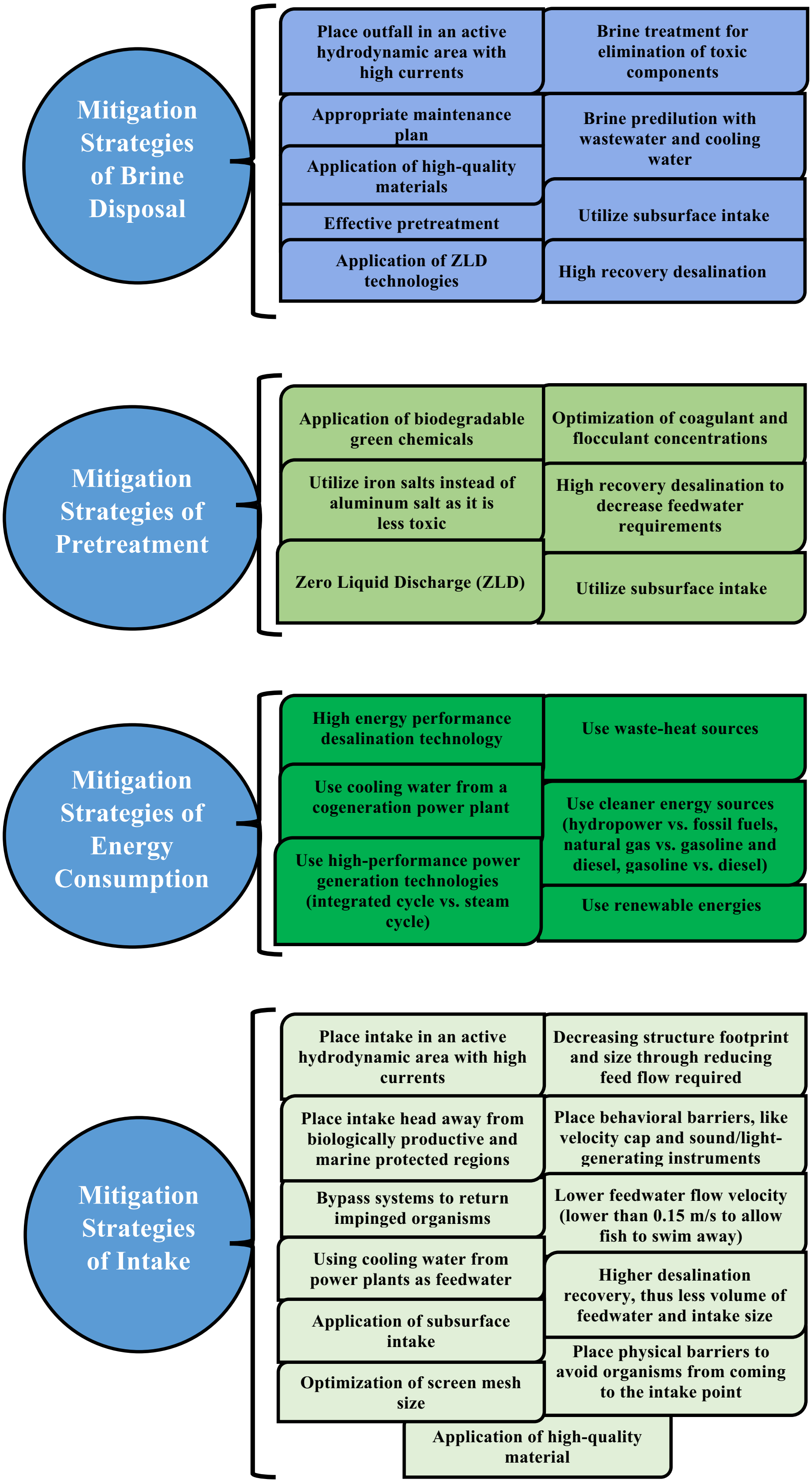
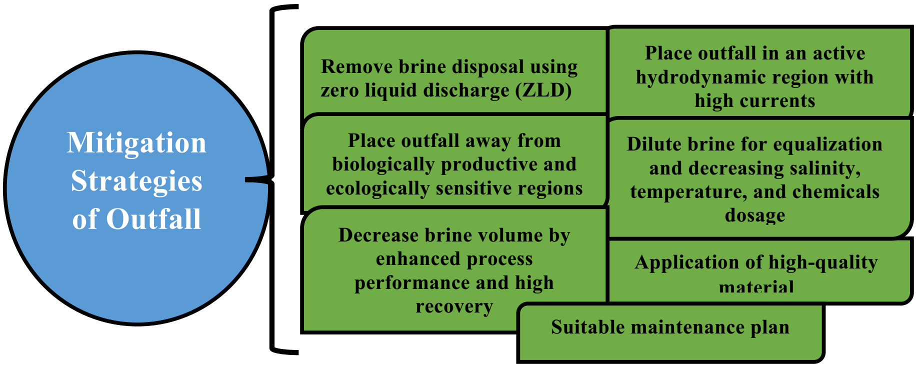


Fig. 10 (continued)



thoroughly explored, as they might decrease the present effects but may endanger alternative new effects. Aiming to reach a watershed concerning eco-friendly and sustainable desalination, the development and application of RES in desalination should take precedence over conventional fossil fuel-based sources. Also, considering public opinion before the construction of desalination plants to reach a profound idea concerning its potential social and environmental effects is crucial. All in all, the above-mentioned strategies will be of great assistance in the mitigation of adverse effects of desalination on the environment. Additional explorations regarding various aspects of desalination, like brine mining schemes, intake systems, diffusers, MLD/ZLD structures, sophisticated designs, membrane fabrications, etc. must be devoted to solving the harmful environmental effects. Moreover, future LCA must be tailored toward innovative technologies for the treatment of brine streams.

Conclusion

Desalination has a decisive role in providing freshwater to mitigate the water shortage challenge over the world. Energy source, desalination technology, and feedwater source are three major parameters that have considerable effects on the overall environmental effects of desalination. Nonetheless, the growing concerns and cogent arguments concerning the negative environmental effects of desalination remain highly contentious. The most suitable choice of desalination method is the central parameter for alleviating the overall environmental effects of desalination because it is the influential element for brine disposal, energy consumption, pretreatment demand, and intake and outfall size. Application of RES, cutting-edge desalination methods, and integrated desalination systems, were the most powerful tools to markedly decrease the environmental footprints of desalination. Summary of mitigation measures for minimizing environmental footprints of desalination is presented in Fig. 10 (Elsaid et al. 2020c). In this paper, the environmental effects of desalination are critically evaluated, and some impact mitigating strategies for safe discharge of reject brine stream are proposed. It goes without saying that present seawater desalination has broad ranges of negligible to extremely negative effects on society, air quality, and marine ecology. Nevertheless, fortunately, there are different feasible strategies to compensate for these negative environmental effects. Technological advancements can play a pivotal role in decreasing these detrimental effects. Moreover, the reject stream can be used for different beneficial applications while at the same time diminishing its harmful effects. It is obvious that with improvements in technical aspects of desalination and the application of RES, reaching pollution-free and sustainable desalination is not unrealistic.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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