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Review

Environmental impacts of desalination and brine treatment - Challenges and mitigation measures

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ABSTRACT

Desalination is perceived as an effective and reliable process for obtaining freshwater from aqueous saline solutions such as brackish water, seawater and brine. This can be clarified by the fact that >300 million people worldwide rely on desalinated water for their daily needs. Although the desalination process offers many advantages, there are rising concerns about possible adverse environmental impacts. Generally, environmental impacts can be generated both in the construction and operation of desalination plants. A major issue of desalination is the co-produced waste called 'brine' or 'reject' which has a high salinity along with chemical residuals and is discharged into the marine environment. In addition to brine, other main issues are the high energy consumption of the desalination and brine treatment technologies as well as the air pollution due to emissions of greenhouse gasses (GHGs) and air pollutants. Other issues include entrainment and entrapment of marine species, and heavy use of chemicals. The purpose of this review is to analyze the potential impacts of desalination and brine treatment on the environment and suggest mitigation measures.

1. Introduction

Water is a vital necessity for human beings and the natural world. Contrary to the saltwater present on planet Earth, the freshwater available to humans is extremely limited, so it is essential to find solutions to increase the amount of water suitable for direct human consumption or to be used in agricultural or industrial activities, and ultimately to meet the world's demand for freshwater. Desalination is considered a reliable and feasible option for meeting the growing demand for water. It is a process of separating the dissolved salts from an aqueous solution (from brackish water up to brine) to obtain freshwater. Currently, desalination is practiced in 150 countries around the world and >300,000,000 people depend on desalinated water for their daily needs (IDA and GWI DesalData, 2019).

It is common that when referring to the desalination process, people think that it is a clean alternative for the supply of drinking water, however, it is an option that, like many others, can have environmental impacts potentials similar to those of any other industry. In addition to freshwater recovery, a discharge stream called 'brine' is co-produced and can be hazardous to the environment as it is a hyper-saline solution and may contain chemicals (e.g., $FeCl_3$, NaOCl $AlCl_3$, H_2SO_4) from the different operations in the desalination plant (Panagopoulos et al., 2019). Currently, brine is disposed of into the marine environment, and several environmental concerns have arisen. Furthermore, desalination technologies are energy-intensive and the energy required is currently produced using fossil fuels. The use of fossil fuels is associated with emissions of greenhouse gasses (GHGs) and air pollutants (Tarnacki et al., 2011; Al-Shayji and Aleisa, 2018). The environmental impacts can be generated both in the construction and operation of desalination plants. Furthermore, the impacts may vary depending on the origin of the feed water or the location of the plant, but for brackish water, seawater or brine it is common for mitigation plans to be very similar.

To date, several reviews on the environmental impacts of desalination plants have been published. Höpner and Windelberg (1997) examined the imaginable environmental impacts of desalination plants on coastal zone ecosystems. In another review article, Sadhwani et al. (2005) focused on the environmental impacts of reverse osmosis (RO) desalination plants in Canary Islands (Spain). Five case-studies were considered in particular, and ecological impact assessments were carried out. Lattemann and Höpner (2008) focused mainly on the environmental impact of brine and chemical discharges to the marine environment, while Roberts et al. (2010) analyzed the environmental and ecological effects of brine discharges in receiving marine waters. Latteman (2010) and Miller et al. (2015) investigated a variety of environmental impacts of seawater desalination. More recently, Shemer and

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Nomenclature

Abbreviations

BC	brine concentrator
BCr	brine crystallizer
ED	electrodialysis
EDM	electrodialysis metathesis
EDR	electrodialysis reversal
EIA	environmental impact assessment
EMPs	environmental monitoring plans
ERD	energy recovery device
EFC	eutectic freeze crystallization
FO	forward osmosis
GHGs	greenhouse gases
HPRO	high-pressure reverse osmosis
LCA	life-cycle assessment
LPRO	low-pressure reverse osmosis
MCr	membrane crystallization
MD	membrane distillation
MED	multi-effect distillation
MSF	multi-stage flash distillation
NF	nanofiltration
OARO	osmotically assisted reverse osmosis
RO	reverse osmosis
SD	spray dryer
SWRO	seawater reverse osmosis
TVC	thermal vapor compression
TDS	total dissolved solids
ZLD	zero liquid discharge

Semiat (2017) assessed the environmental impacts of RO plants and their energy requirements. In addition to the environmental impacts, Lior (2017) studied the economic and social impacts of desalination. Ameen et al. (2018) and Jia et al. (2019) investigated the environmental impacts associated with the GHGs emissions. Sola et al. (2020) examined the efforts made in Spain to mitigate the consequences of brine discharge.

Such reviews, however, do not include recent developments in commercial desalination technologies as well as in new emerging desalination technologies that can be used to treat brine and thus to recover extra freshwater and/or resources such as salts. In addition, recent and advanced mitigation measures have not been reported, as anticipated. Thus, in the present review, the potential environmental impacts of desalination technologies, available to treat from brackish water up to brine, are been analyzed and evaluated, while mitigation measures are suggested. The paper is summarized as follows: desalination technologies and current status are discussed in Section 2, while the environmental impacts of desalination technologies and mitigation measures are discussed in Section 3. Finally, findings and perspectives are presented in Section 4.

1.1. Research methodology

A comprehensive review of the literature was conducted to record, analyze and evaluate the environmental impacts of desalination and brine treatment. Search engines of databases such as Google Scholar, SCOPUS, and Science Direct were used. Keywords such as "desalination environmental impacts", "desalination environmental concerns", "brine discharges", "marine pollution desalination plants", "brine treatment environmental impacts", "desalination plant environmental impact assessment", "desalination life-cycle assessment", "desalination environmental monitoring plans" were selected as search terms. Research on emerging desalination and brine treatment technologies, as well as systems/methodologies to minimize energy consumption and air pollution have also attracted substantial attention. In addition, research studies on the marine environment and resource recovery were reviewed due to the complexity of the research topic. 783 publications were found in the primary search attempts (323 papers in Google Scholar, 245 in SCOPUS, and 215 papers in Science Direct). However, there was a degree of overlap between the three databases as observed. When duplicates were deleted, 304 papers remained. Papers were excluded if they were (i) published in a language different from English and (ii) published before 25 years. After this filtering work, 175 papers from 1997 to 2020 remained for the analysis. In particular, 30 publications were about desalination technologies, 64 publications were about brine discharge, 24 publications were about energy consumption and air quality, 17 publications were about intake activity, 8 publications were about plant construction and social impact, while 32 publications were about more than one aspect. The key results were gathered and analyzed from each research study/review, while the problems and recommendations for future research were also established by highlighting the limitations of the selected research studies.

2. Desalination-current status and technologies

Desalination is a term used to describe the process of producing freshwater out of saline water (brackish water, seawater or brine). In more detail, the desalination is a procedure that is performed on an aqueous solution to separate the salts from the solution or to separate the water from the salts; however, the exact procedure depends on the type of technology used (Panagopoulos et al., 2019). The freshwater produced should contain a content of total dissolved solids (TDS) that is appropriate for domestic or industrial use. Specifically, although there is no worldwide regulation on the freshwater purity for human consumption, it is suggested that drinking water should contain <500 mg/L TDS (Rosborg, 2019; European Community, 1998). On the other hand,

Table 1
Composition of brackish water, seawater and brine.

Saline solution	Total dissolved solids (TDS) (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^{-} (mg/L)	PO_4^{3-} (mg/L)	References
Brackish water	2480	230	66.8	142	–	382	72.4	–	–	(Wright et al., 2018)
Brackish water	1691.4	102	78.5	340	6	645	80	350	–	(Sweity et al., 2015)
Seawater	34,483	400	1262	10,556	380	18,980	2649	140	–	(Magazine – Water Condition and purification, 2005)
Seawater	39,017	474	1356	12,245	434	21,535	2772	146	–	(Waly et al., 2012)
Brine	57,400	521	1738	18,434	491	32,127	4025	–	2.5	(Kayvani Fard et al., 2016)
Brine	70,488	790	2479	21,921	743	38,886	5316	173	–	(Gude, 2018)

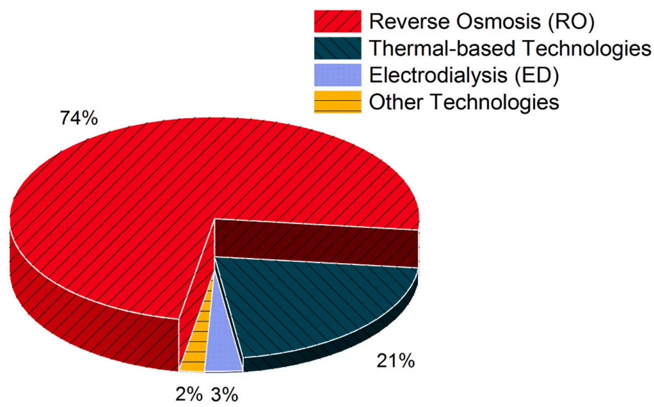

Fig. 1. Desalination technologies used at plants worldwide in 2019. The technologies include reverse osmosis (red pie slice), thermal-based technologies (green pie slice), electrodialysis (light blue pie slice) and other technologies (light yellow pie slice). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

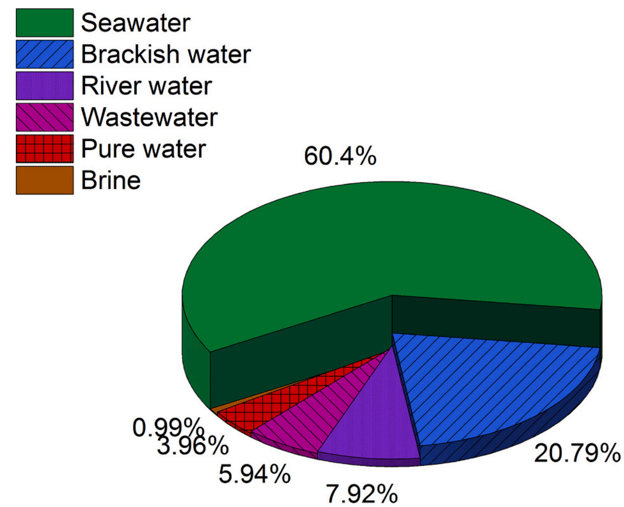

Fig. 2. Types of feed water used in desalination plants.

the purity of the water has to be much higher (10–20 mg/L TDS) in many industrial applications such as pharmaceuticals, semiconductors, etc. (Agalloco and Carleton, 2007; Reinhardt and Reidy, 2011). Besides freshwater, a by-product called 'brine', 'reject' or 'concentrate' is produced. The by-product is at least 1.6 times more saline than seawater (Table 1) and its management is a crucial issue as brine has adverse effects on the environment (Heck et al., 2016; Missimer and Maliva, 2018; Frank et al., 2017). Overall, input streams include feed water, energy and chemicals; while output streams include freshwater produced, brine and GHGs emissions.

The desalination technologies can be classified into two major categories: (i) thermal-based technologies and (ii) membrane-based technologies (Panagopoulos et al., 2019; Al-Sahali and Ettouney, 2007). In thermal-based technologies, thermal energy (heat) is required to achieve the desired separation in distillations or evaporations. Such technologies mimic the natural water cycle, as the aqueous solution evaporates and then the vapor produced condenses as freshwater (Wang et al., 2016). Thermal-based technologies that are most commercially successful are multi-effect distillation (MED) and multi-stage flash distillation (MSF) (Al-Gobaisi, 2010). The membrane-based technologies, on the other hand, are mainly non-phase-transition technologies. Semipermeable membranes are used particularly in these technologies to retain salts and purify the water that penetrates them. The separation is accomplished by making use of electrical energy to achieve the desired external pressure (Nagy, 2019; Tado et al., 2016). The most commercially successful membrane-based technologies are RO, nanofiltration (NF), electrodialysis (ED) and electrodialysis reversal (EDR) (Panagopoulos et al., 2019).

Currently, the total desalination capacity installed worldwide stands at around 21,123 plants, producing approximately 142,000,000 m^3/day of freshwater (IDA and GWI DesalData, 2019). It is interesting to mention that the aforementioned amount of freshwater produced per day is significant as it is equivalent to the water volume of 56,800 Olympic-sized swimming pools. Most countries systematically use desalination, with most desalination plants in Saudi Arabia, the United States of America, the United Arab Emirates, Kuwait, France, Japan, etc. (Eslamian, 2016; IDA and GWI DesalData, 2019). Currently, the largest desalination plant is the Jubail Plant (Saudi Arabia) which produces 1,401,000 m^3/day of freshwater (Guinness World Records, 2019). According to Fig. 1, RO technology is the most prevalent, with 74% of the world's installed capacity using this technology in 2019, while another 21% and 3% remained in the use of thermal technologies (namely, MED and MSF) and ED, respectively; the remaining 2% refers to technologies that they were unable to dominate the market due to their costs and/or existing technical constraints (IDA and GWI DesalData, 2019). RO's dominance over the last decade can be attributed to its efficiency, scalability and modularity as there have been many advancements over the last decade (Kucera, 2015; Trishitman et al., 2020). Typically, the mature desalination technologies are primarily used in the desalination of brackish water and seawater. This current status can be clarified by Fig. 2 (Gude, 2018; Kucera, 2019). As illustrated in Fig. 2, the majority of the desalination plants (>80%) desalinates brackish water or seawater. Concerning brine, the percentage is insignificant (<1%). However, technologies have been developed exclusively for the treatment of desalination brine, such as brine concentrator (BC), brine crystallizer (BCr), spray dryer (SD) (GEA Process Engineering, 2019; Kerone, 2018; Veolia Water Technologies, 2018). The reason behind this is that brine treatment is an upcoming sector of the water treatment industry since it is possible to recover higher volumes of freshwater and resources (e.g., salts) (Panagopoulos et al., 2019). Moreover, new and emerging technologies that can be used on saline solutions (from brackish water up to brine) have been recently developed. Such technologies include forward osmosis (FO), membrane distillation (MD), membrane crystallization (MCr) electrodialysis metathesis (EDM), osmotically assisted reverse osmosis (OARO), eutectic freeze crystallization (EFC), high-pressure reverse osmosis (HPRO), etc. (Ashoor et al., 2016; Václavíková et al., 2017; Ahmed et al., 2018; Chen and Yip, 2018; Chivavava et al., 2014; Bartholomew et al., 2017; Ali et al., 2015). Overall, desalination and brine treatment technologies are summarized in Fig. 3.

3. Environmental impacts and mitigation measures

The vast majority of industrial processes have both positive and negative impacts on the natural environment and society. Therefore, if there is an alteration to the natural environment, either by a human or by nature, we experience an impact on the environment (Goudie, 2018). The same behavior is observed at desalination. Desalination process involves different activities, some of which take place only during plant construction (e.g., construction of electricity and sewerage networks), while others are present during plant lifetime (e.g., pretreatment and post-treatment) (Peters and Pintó, 2008; Galanakis and Agrafioti, 2019). In particular, activities such as clearance and grading of the project area, connection to electricity and sewage networks, construction of facilities and access roads, feed water intake, by-product discharge, storage and transport of desalinated freshwater, use of pretreatment and post-treatment chemicals, noise and vibration, etc. change the natural state of the environment and may have an adverse impact (Wetterau, 2011; Missimer et al., 2015). Given that desalination plant lifetime ranges from 20 years to 35 years, it is easy to understand that environmental

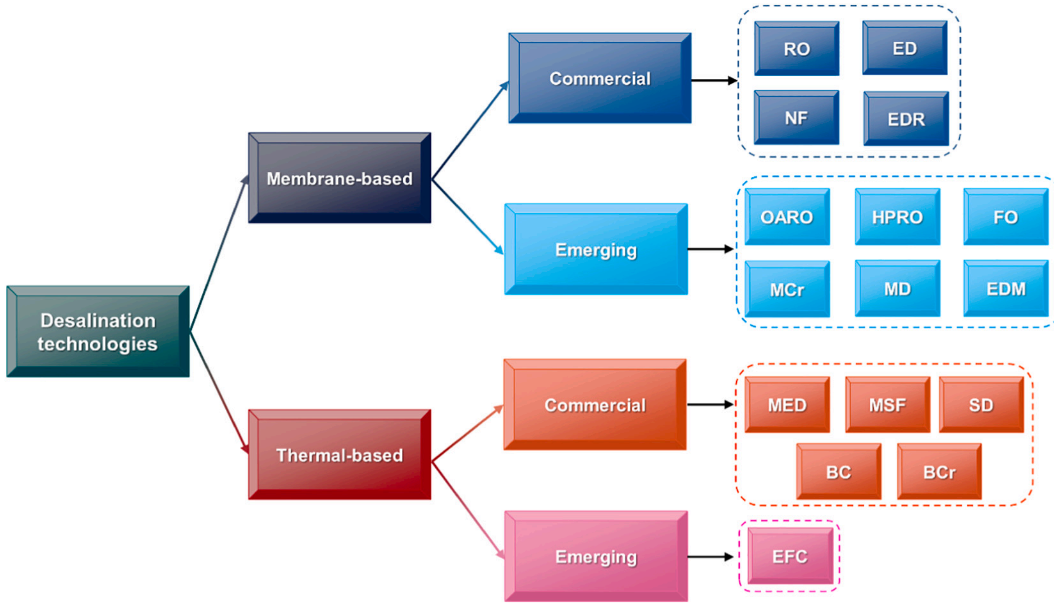

Fig. 3. Classification of the desalination and brine treatment technologies. In addition, the technologies are classified as membrane-based or thermal-based technologies, and as commercial or emerging technologies.

aspects are equally important as the commercial aspects and should therefore be considered a desalination plant's design factor (Panagopoulos et al., 2019; Olabarria, 2015). In addition, compliance with the environmental legislation allows for the avoidance of economic penalties and operational limitations that can cause substantial monetary losses in the desalination plant. Therefore, the major environmental impacts are as follows: (i) major adverse effects on the quantity and quality of natural resources, including soil, air and water (ii) substantial changes in aquatic ecosystems and human resettlement (ii) heavy use of chemical products near urban or rural areas (iv) public health risk due to the quantity and quality of effluents, emissions or residues (v) landscape alteration (Dawoud, 2012; Höpner and Windelberg, 1997; Karbassi et al., 2010; Missimer and Maliva, 2018; Sadhwani et al., 2005; Younos, 2005).

3.1. Brine discharge on the environment

Brine is the waste product of desalination and several researchers have assessed its potential impact on the environment (Gacia et al., 2006; Matsumoto and Martin, 2008; Cooley et al., 2013; Brika et al., 2015; de-la-Ossa-Carretero et al., 2016; Fernández-Torquemada and Sánchez-Lizaso, 2005). According to the author and assuming an average freshwater recovery of 40%, we can estimate that desalination plants produce approximately 128,652,000 m^3/day of brine worldwide. The quality and quantity of the brine are directly dependent on the technology adopted, the quality of the feed water, the standards that must be met by the freshwater produced, the pretreatment and post-treatment operations, and the manner that the equipment is cleaned and maintained. In addition, brine may include residuals from different chemicals e.g., antiscalants (polyphosphates, phosphonates and polycarbonic acids), flocculants (cationic polymers) and coagulants ($FeCl_3$, $Fe_2(SO_4)_3$), in several stages of the desalination process, such as equipment washing, pretreatment or post-treatment operations, which can be particularly detrimental to the health of marine organisms (Gude, 2018; Panagopoulos et al., 2019; Cooley et al., 2013). Brine salinity produced by membrane-based technologies, mainly seawater reverse osmosis (SWRO), ranges from 60 g/L TDS to 85 g/L TDS, while brine salinity produced by thermal technologies (i.e., MSF and MED) ranges from 55 g/L TDS to 65 g/L TDS, respectively. Compared to thermal-based plants, this differentiation can be attributed to the higher recovery rates (40–45%) present in commercial and well-established RO plants. With respect to salinity in brine treatment, salinity depends on the recovery of the treatment-related technology (or technologies) and can be much higher than 150 g/L TDS (Panagopoulos et al., 2019; Panagopoulos, 2020a). For example, McGinnis et al. (2013) used FO and concentrated a brine solution from 73 ± 4.2 g/L TDS to 180 ± 19 g/L TDS. As for the temperature of the brine, membrane-based plants produce brine at ambient temperature, much like the temperature of the feed water. In particular, a maximum difference of 1–2.5 °C has been reported, which could be from heat dissipation in the pumps and/or friction in the channels of the RO elements (Nagy, 2019; Spellman, 2015). MD and MCr are the only exceptions in membrane-based technologies, as these technologies are thermal-driven and produce brine at significantly higher temperatures (>30 °C). On the other hand, thermal-based plants produce brine of higher temperature (25–40 °C) than the ambient temperature as evaporation takes place (Cambridge et al., 2017; Missimer et al., 2015).

Table 2
Summary of the brine disposal methods. The methods include sewer discharge, evaporation pond, surface water discharge, deep-well injection and land application (Panagopoulos et al., 2019).

Method	Principle	Cost (US $/m^3_{brine rejected}$)	Environmental challenges
Sewer discharge	Brine is rejected in a sewage collection system	0.32–0.66	Inhibition of bacterial growth in the wastewater treatment plant
Evaporation pond	Brine is evaporated in a pond and the residual salts are gathered	3.28–10.04	Groundwater pollution and soil salinization
Surface water discharge	Brine is rejected into the surface water	0.05–0.30	Marine environment pollution
Deep-well injection	Brine is injected into porous subsurface rock formations	0.54–2.65	Groundwater pollution and soil salinization
Land application	Brine is used in irrigation of salt-tolerant crops and grasses	0.74–1.95	Soil salinization

To address this waste from the process, desalination plants adopted several brine disposal (also called discharge) methods. These methods include sewer discharge, evaporation ponds, surface water discharge, deep-well injection and land application (Panagopoulos et al., 2019; Mickley, 2018; Ziolkowska and Reyes, 2016). Table 2 presents a summary of the disposal methods and their challenges. As can be seen from Table 2, there is no single disposal method that has only advantages. For example, deep-well injection is unsuitable for countries with high seismic activity (e.g., Greece), evaporation pond is the costliest method since it requires high footprint area, sewage discharge and land application can only be used for small amounts of brine, and surface water discharges have a direct impact on the marine environment (Panagopoulos et al., 2019). Therefore, even with the adopted disposal methods, brine may have an adverse impact on the environment.

Regarding the potential impact on the marine environment, even a single plant can have an impact on the marine environment if proper measures have not been applied as brine discharges produce local impacts. These impacts can be more severe when many desalination plants operating on the same coastline discharge brine without sufficient measures (Kress, 2019). As previously mentioned, brine is a denser solution than seawater as it has a salinity at least 1.6–2.1 times higher than seawater and several studies have indicated that a change in the salinity of the water may affect the marine species (Zacharias and Ardron, 2019; de-la-Ossa-Carretero et al., 2016; Drami et al., 2011; Clark et al., 2018; Frank et al., 2019; Belkin et al., 2017; Panagopoulos et al., 2019). In particular, the most significant impact that may occur on marine species such as fishes, plankton, algae, seagrass, etc. is the 'lethal osmotic shock' due to irreversible dehydration of their cells (Abushaban, 2019; Levitt, 2015). As a consequence of dehydration, there is a reduction in turgor pressure that could result in the long-term extinction of the marine species (Belkin et al., 2017).

Several studies have assessed the impact of brine on seagrass species such as *Posidonia oceanica* or *Cymodocea nodosa*. With respect to *P. oceanica*, laboratory experiments have shown that salinities higher than 39.1 mg/L lead to a reduction in seagrasses vitality in terms of leaf grow, necrotic spots, and leaves premature senescence. In addition, about 50% of seagrasses died in a time span of 2 weeks when *P. oceanica* was exposed to 45 mg/L (Fernández-Torquemada and Sánchez-Lizaso, 2005). Similar results have been observed for *C. nodosa* (commonly found in the Mediterranean Sea) as this seagrass was adversely affected by increased salinity in both laboratory conditions and in situ transplantation nearby brine discharges (Garrote-Moreno et al., 2014). Compared with *C. nodosa* and the Mediterranean species *P. oceanica*, which are significantly sensitive to hyper-saline concentrations caused by brine plumes, other species such as the Australian species *Posidonia australis* present a wide range of salinity tolerances ranging from 27 g/L up to 60 g/L (Garrote-Moreno et al., 2015; Cambridge and Kendrick, 2009; Sandoval-Gil et al., 2012; Garrote-Moreno et al., 2014; Cambridge et al., 2019; Sanchez-Lizaso et al., 2008). Cambridge et al. (2017) found out that *P. australis* is tolerant of high salinity conditions for a substantial period, in particular for up to 2 weeks at maximum investigated salinity (54 g/L) and for >6 weeks at moderate salinity (46 g/L).

Only a few studies have assessed the effect of brine on benthic fauna, such as echinoderms and polychaeta. Echinoderms are one of the main bioindicator species studied regarding brine discharges impacts on the marine environment from RO plants (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013). A recent study has shown that desalination concentrates can affect benthic bacteria in a site-specific and localized manner, where the disposal options and local stressors (e.g., elevated water temperature and eutrophication) have affected the abundance and diversity of these communities (Frank et al., 2017). In another study, Petersen et al. (2018) observed different levels of salinity tolerances in coral reef-building species. Furthermore, the results of the study revealed that increased salinity (10% above ambient) altered the coral's physiology and visual appearance.

Jenkins et al. (2012) mentioned that differentiation in the salinity of the water by 2–3 parts per thousand can harm some species, whereas other species remained unharmed to alterations in the salinity. In particular, marine organisms with a narrow tolerance range in salinity changes (e.g., goldfish) are called 'stenohaline' whereas organisms with a wide tolerance range in salinity changes (e.g., molly fish) are called 'euryhaline' (Formicki and Kirschbaum, 2019; Flügel, 2013). Regardless of the type of marine species (stenohaline or euryhaline), it is important to mention that a wide range of organisms may temporarily adapt to unusual salinity and temperature conditions, but when exposed to extreme and unfavorable conditions, the abundance of fauna and flora will be affected, and in some occasions, changes in the ecosystem may attract other unusual species in the region under normal conditions. Kress et al. (2020) found out that the rejected brine can increase the temperature of seawater by up to 0.7 °C.

Apart from salinity, heavy metal and residues of chemicals present in brine can have a harmful impact on the marine species. The presence of heavy metals in the discharge areas is mainly associated with thermal-based technologies (e.g., MSF or MED) which, due to the high process temperatures, may cause corrosion of some metal equipments. In particular, heavy metals such as Cu and Ni may be present when Cu—Ni alloys of heat exchangers and pumps start to wear out (Panagopoulos et al., 2020). However, pollution with such heavy metals in membrane-based technologies (e.g., RO or NF) is typically below critical levels since non-metallic materials (e.g., polymers) are mainly used in membrane-based plants (Kucera, 2015; Nagy, 2019). In a recent study, Zhou et al. (2013) presented an average concentration of heavy metals in seawater RO brine: Fe (0.4 ± 20% μg/L), Ni (3 ± 20% μg/L), Cr (3.5 ± 20% μg/L), Pb (0.13 ± 20% μg/L) and Cu (15 ± 20% μg/L). However, according to literature, these concentrations of heavy metals are much lower than toxic levels for certain species in aquatic environments (Furness, 2018; Gheorghe et al., 2017). More recently, Alshahri (2016) and Alharbi et al. (2017) found high Cu concentrations in the coastlines of the Arabian/Persian Gulf; however, these concentrations may be attributed to anthropogenic activity and not particular to brine discharges, as no further scientific evidence has been published that a brine discharge from an RO plant produces heavy metal accumulations in the region.

Impacts on the marine environment are potentiated when the brine discharges meet with highly sensitive ecosystems. The magnitude of the impact depends on both the physicochemical characteristics of the desalination brine as well as the hydrographic and biological conditions of the ecosystem that receives the discharge. Closed, semi-closed and shallow places, with an abundance of marine life, are susceptible to stronger impacts on the ecosystem's health. Such places are the semi-closed seas, the Red Sea (438,000 km^2) and the Mediterranean (2,500,000 km^2), where an alteration in the salinity can be significant (Williams and Follows, 2011). On the other side, in places with abundant ocean currents such as Australia, negligible impacts have been indicated in the marine environment (Sydney Water, 2005; Chevron Australia, 2015). An environmental impact assessment (EIA) should be conducted to resolve the environmental impacts associated with desalination plants. EIA provides a series of studies and management processes to assess the appropriate location for desalination facilities, and also preventive and corrective steps to mitigate environmental effects on marine and coastal environments (Alonso and Melián-Martel, 2018; Sola et al., 2019b). Environmental monitoring plans (EMPs) are developed within the EIA to assure the efficacy of preventive and corrective steps to secure the marine environment from the adverse effects of brine discharge and to take protective actions when environmental damage is observed (Sola et al., 2019a; Sola et al., 2019b; Sola et al., 2020).

Furthermore, to comply with the environmental regulations and avoid the environmental impact from the disposal of brine in the water bodies (from river to ocean), the outfalls of desalination plants should be dimensioned appropriately to have minimal impact. In particular, the desalination outfalls should dilute the brine as efficiently as possible (Shrivastava and Adams, 2019). To this end, near-field modeling approaches (e.g., CORMIX, VISUAL PLUME, and VISJET) as well as far-field modeling approaches (e.g., Delft3D and MIKE 3) were developed to predict the discharged brine's diffusion and mixing behavior (Palomar et al., 2012; Kress, 2019). In a recent study, Wood et al. (2020) reported that the dilution of brine with cooling water from power plants restrains the formation of density currents. As suggested, a 40-times dilution of the reject effluent appears to be sufficient to protect the 99% of the marine organisms (Falkenberg and Styan, 2015). In addition, the impact of brine disposal can be reduced using multiport diffusers (Del-Pilar-Ruso et al., 2015; Portillo et al., 2012). Portillo et al. (2014) reported the integration of a diffusion system with Venturi eductors improved the dilution process and minimized the adverse effect on marine environment. Significant work has been carried out in recent years to produce new diffuser systems and upgrade existing diffuser systems (Abessi and Roberts, 2017; Roberts, 2015).

In regards to the composition of the brine, the use of polyphosphonate-based antiscalants leads to the discharge of phosphorus into the marine environment. To reduce the discharge of phosphorus, it is recommended to use novel green antiscalants, as they include biodegradable substances (Pervov et al., 2018). With regard to the heavy metals that may be found in the brine solutions due to the corrosion of the metallic equipment (primarily in thermal-based plants), a mitigation measure would be to use more corrosion-resistant materials. Such corrosion-resistant materials are super duplex stainless steel, hyper duplex stainless steel and titanium (SANDVIK, 2019; SANDVIK, 2018). However, their price is significantly higher (at least 1.6 times) than the common metallic materials used now in the thermal-based desalination industry (Panagopoulos et al., 2020). It is worth noting that in systems for desalination brine treatment the use of high-resistance materials is mandatory as high concentrations of Cl^- are very detrimental (Panagopoulos, 2020b). Furthermore, in the thermal-based desalination plants where metallic materials are mainly used, chemicals called 'corrosion inhibitors' are added in the feed water to reduce the corrosion rate of the metallic equipment. However, those chemicals are toxic and thus can contaminate the environment (Liang et al., 2018; Sanni and Popoola, 2019). To this end, it seems promising to use green corrosion inhibitors that can be generated from natural resources, biomass waste, etc. Green corrosion inhibitors are non-toxic and environmentally friendly; however, scientific studies should be performed to determine the effectiveness of these alternative corrosion inhibitors in the desalination industry (Parthipan et al., 2018; Liyanaarachchi et al., 2014; Vasyliev and Vorobiova, 2019).

On the other hand, when brine is disposed of on the dry soil of the evaporation pond, due to the high salinity, the soil structure may deteriorate science Ca^{2+} is replenished by Na^+ in the exchangeable ion complex (Heck et al., 2016; Maliva and Missimer, 2012). Furthermore, the disposal of brine on the evaporation pond may lead to a degradation of the visual appearance. As for the deep-well injection method, it may harm the underground soil or even contribute to groundwater pollution if an underground water aquifer exists. Recently, Nanayakkara et al. (2020) recently studied the environmental impacts associated with the disposal of brine from a low-pressure reverse osmosis (LPRO) plant at Anuradhapura (North Central Province, Sri Lanka). The findings showed higher pH and lower K^+ values in the affected soils compared to non-affected soils, indicating an exchange of H^+ and K^+ ions present in soil with Ca^{2+} and Mg^{2+} present in brine.

Brine is commonly only disposed of as waste through conventional brine management with disposal methods; however, brine can be a resource for both freshwater and useful materials. A more advanced approach to brine management involves brine treatment through the framework of minimal/zero liquid discharge (MLD/ZLD) and mineral recovery (brine mining). Two or more desalination technologies are integrated under a MLD/ZLD scheme to recover higher volumes of freshwater, reduce the brine volume, and produce a solid salt (Panagopoulos et al., 2019; Liu et al., 2016; Panagopoulos and Haralambous, 2020). Liu et al. (2016), for example, suggested an NF-ED hybrid process

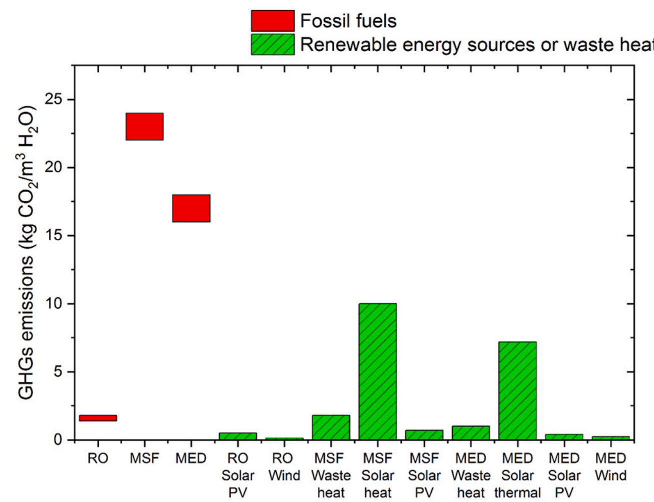

Fig. 4. GHGs emissions per m^3 of freshwater produced by the major desalination technologies when fossil fuels are used (red bars) and GHGs emissions per m^3 of freshwater produced by the major desalination technologies when renewable energy sources or waste heat are used (green bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to concentrate brine. When the technologies are combined in hybrid configurations to enable brine mining, multiple high-purity solid salts can be recovered instead of a single mixed solid salt. Such solid salts include NaCl, $MgCl_2$, $CaCl_2$, etc. (Al Bazedi et al., 2013; Panagopoulos, 2020c; Panagopoulos et al., 2019). The recovery of both freshwater and solid salts can make desalination more economically sustainable due to the additional profit. Nevertheless, brine treatment and brine mining are desalination processes at higher salinities, and thus remain the drawbacks of high energy consumption and GHGs emissions (see Section 3.2).

3.2. *Energy consumption and air quality*

Energy is an important aspect in the environmental assessment at desalination plants. Total energy demand includes the energy required for desalination process, freshwater and brine transportation, plant lighting, office equipment, etc. Since the implementation of desalination on an industrial level, the high energy consumption required has been one of the major obstacles. Indicatively, the energy consumption of RO was 16 kWh/m^3 in the 1970s (Lazarova et al., 2012). Generally, membrane-based technologies (e.g., RO) require considerable amounts of electrical energy to operate, whereas the required amount of energy is much higher in thermal-based technologies (e.g., MED), since thermal energy is needed in these phase-transition technologies (Panagopoulos et al., 2019). Nonetheless, in both cases, fossil fuels produce usually the energy required. The use of fossil fuels to generate the necessary energy is associated with emissions of GHGs. Fig. 4 (red bars) presents the GHGs emissions per m^3 of freshwater produced by the major desalination technologies when fossil fuels are used (Kucera, 2019; Chua and Rahimi, 2017). The thermal-based technologies, namely MSF and MED, have at least ten times higher GHGs emissions than RO, as can be seen from Fig. 4. Consequently, desalination has significant environmental impacts on air quality. It noteworthy to mention that several life-cycle assessment (LCA) studies were conducted to analyze desalination technologies' GHGs emissions. However, these studies focused on the desalination of brackish water/seawater and the major technologies (RO, MSF, MED, ED/EDR) (Altmann et al., 2019; El-Nashar, 2008; Heihsel et al., 2019; Mannan and Al-Ghamdi, 2019; Mannan et al., 2019; Raluy et al., 2006; Raluy et al., 2005; Tarnacki et al., 2011; Zhou et al., 2014). For better insight, therefore, future LCA studies should focus on both brine treatment and emerging desalination technologies. The

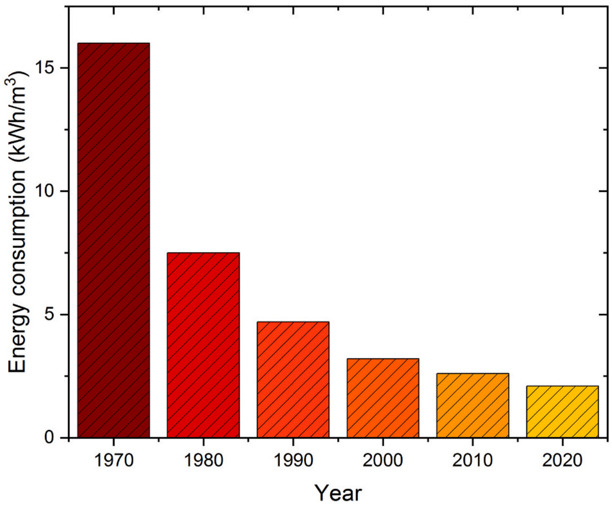

Fig. 5. The reduction in the energy consumption of RO. The bars indicate the minimum reported energy consumption of RO in each time period.

Table 3
The energy consumption of desalination and brine treatment technologies (Panagopoulos et al., 2019; Ali et al., 2015; Ihm et al., 2016; Fluid Technology Solutions Inc., 2016; GEA Process Engineering, 2019; Schantz et al., 2018; Chivavava et al., 2014; Bartholomew et al., 2017; Lokare et al., 2018).

Technology	Energy consumption (kWh/m^3)
Membrane distillation (MD)	39–67
Spray dryer (SD)	52–64
Osmotically assisted reverse osmosis (OARO)	6–19
Brine concentrator (BC)	15.86–26
Multi-stage flash distillation (MSF)	12.5–24
Membrane crystallization (MCr)	39–73
EFC (Eutectic freeze crystallization)	43.8–68.5
Forward osmosis (FO)	0.8–13
Electrodialysis (ED) & Electrodialysis reversal (EDR)	7–15
High-pressure reverse osmosis (HPRO)	3–9
Reverse osmosis (RO) & Nanofiltration (NF)	2–6
Brine crystallizer (BCr)	52–70
Multi-effect distillation (MED)	7.7–21
Electrodialysis metathesis (EDM)	0.6–5.1

massification of this alternative process to obtain freshwater has encouraged the reduction of these disadvantageous aspects. In particular, the energy consumption of RO has been reduced from 16 kWh/m^3 in the 1970s to 2 kWh/m^3 in 2020 (Fig. 5) (Lazarova et al., 2012; Panagopoulos et al., 2019). This significant reduction in RO energy consumption can be attributed to advances in membrane materials as well as in energy recovery devices (ERDs), such as pressure exchangers, energy recovery turbines, etc. (Nagy, 2019). With regard to the other major desalination technologies, the energy consumption of ED is nowadays 7–15 kWh/m^3, of MED is 7.7–21 kWh/m^3 and of MSF is 12.5–24 kWh/m^3 (Ihm et al., 2016; Deyab, 2019; Zhao et al., 2019; Yan et al., 2018; Reig et al., 2014; Panagopoulos et al., 2019). In more detail, the energy consumption of desalination technologies is presented in Table 3. The energy consumption ranges can be clarified by the variation in both the salinity of the feed water and the efficiency of each technology. It is worth noting that desalination technologies such as BCr, MCr, EFC and SD used to crystallize the brine (>200 g/L TDS) consume >40 kWh/m^3 of energy. In general, the higher the feed water salinity (from brackish to brine), the higher the energy consumption. To have a better view of the energy consumptions, it is interesting to note that the energy needed to obtain 10 L of freshwater through RO (at the energy consumption of 6 kWh/m^3) is equivalent to the power required in a 60-watt incandescent bulb that operates for 1 h.

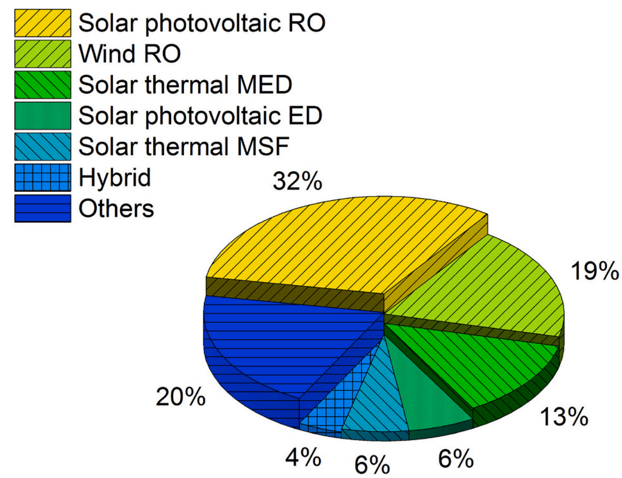

Fig. 6. Desalination technologies coupled with renewable energy sources at plants worldwide.

Despite the recent advancements in desalination technologies, the desalination process is still energy-intensive and thus the energy consumption should be reduced. The energy consumption mitigation measures according to the author are as follows: (i) coupling desalination plants with renewable energy sources such as solar energy, geothermal energy, wind power, tidal power or other alternative energy sources such as waste heat from industrial processes (Sharon and Reddy, 2015; Segurado et al., 2016; Turchi et al., 2017; Abdelkareem et al., 2018; Ishaq et al., 2018). As compared to fossil fuels, renewable energy sources are abundant and more sustainable. Moreover, Fig. 4 (green bars) presents the GHGs emissions per m^3 of freshwater produced by the major desalination technologies when renewable energy sources or waste heat are used. As shown in Fig. 4, GHGs emissions are significantly lower when using renewable sources of energy or waste heat. Fig. 6 shows the desalination plant types which are based on renewable energy sources (Gude, 2018). As shown in Fig. 6, solar energy is the most used renewable energy in the desalination plants. At present, the number of desalination plants based on renewable energy sources is extremely low (<1%) due to high capitals costs compared to the conventional plants powered by energy from fossil fuels (Mahmoudi et al., 2017). The largest desalination plant based on renewable energy sources is the Al Khafji Solar Saline Water RO in Al Khafji, Saudi Arabia. With regard to the technical characteristics of the plant, its energy consumption is 3.7 kWh/m^3 and its technology is solar photovoltaic RO. Its capacity is 60,000 m^3/day of freshwater which is 24 times lower than the capacity of the largest desalination plant powered by fossil fuels (TAQNIA, 2019). Another challenge is that not every form of renewable energy is always available in every area. For example, in countries with high solar irradiance such as the United Arab Emirates (5.72–6.18 kWh/m^2) solar power can be used efficiently compared to countries with low solar irradiance such as Norway (1.95–3.05 kWh/m^2) (Global Solar Atlas, 2020). Nevertheless, more desalination plants based on renewable energy will be constructed in the future, as incentives will be given in, for example in the European Union countries (European Parliament, 2020). It is worth mentioning that despite the reduction in GHGs emissions, the energy consumption is not reduced as the consumption depends significantly on the core of each technology (ii) applying co-generation that consists of simultaneously obtaining and utilizing electrical and thermal energy, significantly increases the plant's energy efficiency (El-Nashar, 2008; Altmann et al., 2019). For example, Jubail IWPP Plant in Saudi Arabia is an integrated water and power plant with a production capacity of 800,000 m^3/day of freshwater and 2745 MW of power, using MED-TVC technology. Several researchers have investigated cogeneration systems such as CO_2 Brayton cycles and MED desalination systems,

Table 4
Classification of the water intake systems. In addition, the systems are classified as surface intake systems and subsurface intake systems.

Intake system	Classification	Subclassification
Surface	- Surface water intake - Deep water intake	–
Subsurface	Well system	- Vertical wells - Radial collector wells - Angle wells - Horizontal wells
	Gallery system	- Beach galleries - Seabed galleries

organic Rankine cycle and MSF desalination systems, etc. (Kouta et al., 2016; Sharon and Reddy, 2015). Furthermore, some desalination technologies are self-sufficient and use excess energy from one stage of the cycle to lower pressure or boost temperature at another stage, such as in the thermal-based technologies, MSF and MED (iii) efficient energy usage plan: in every desalination plant, a plan for energy conservation and reduction of consumption is advised.

3.3. Intake activity

Besides energy consumption and GHGs emissions, the impact of the water intake activities in the desalination plants should be assessed. The water supply systems are the first main element of the desalination plant because the plant needs to be continuously and properly supplied with brackish water/seawater. Water intake systems can usually be classified into two major categories: (i) surface intake systems and (ii) subsurface intake systems (Table 4). Feed water is obtained from the open surface in the first category, while in the second, the feed water is obtained from infiltration galleries, vertical wells, or other places under the seabed (Dehwah et al., 2015; Pankratz, 2004). In the majority of seawater desalination plants, surface water systems are used due to their capacity to pump vast volumes of feed water, as well as due to their ease of construction and low cost (Pankratz, 2015; WateReuse Association, 2011). Nevertheless, the quality of the feed water is not stable due to seasonal variations. Additionally, the presence of large amounts of algae may lead to a temporary shutdown of the desalination plant (Villacorte et al., 2009; Nagaraj et al., 2018). For example, due to harmful algal blooms in 2009, the Galeelah Desalination Plant (UAE) equipped with surface water intakes was shut down (Berktay, 2011; Ismail, 2009).

As for the environmental impact, the use of such intake systems can result in marine species being trapped on the suction racks, resulting in injury or death. In addition to the environmental impact, the entrapment of marine species leads to a need for a more intensive pretreatment, which increases both energy consumption and economic costs (Henthorne and Boysen, 2015; Villacorte et al., 2015). For this reason, using subsurface intake systems can reduce the negative environmental impact. Through subsurface intake systems, there is no entrainment of marine species (Rachman et al., 2014; Dehwah and Missimer, 2016). At the same time, less or even no chemical additives are required during the pretreatment stage, as well as less energy. Desalination plants with subsurface intake systems, however, are significantly few compared to those using surface intake systems, as subsurface intake systems are site-specific, more expensive, and permits are difficult to be obtained (Missimer et al., 2013; Dehwah and Missimer, 2016). Recently, Al-Kaabi and Mackey (2019a, 2019b) conducted an LCA study to examine the environmental effects of surface and subsurface intake systems for two SWRO plants with operating capacities of approximately 175,000 m^3/d and 275,000 m^3/d. Results revealed that surface intake had higher environmental consequences than subsurface intake among all impact categories, while subsurface intake presented a significant energy reduction of 30% (Al-Kaabi and Mackey, 2019a, 2019b). Mitigation measures for the impacts of intake activity are as follows: (i) locating intake areas in a region that does not have a critical impact on ecological communities (ii) promoting low speeds (<0.20 m/s) in channels to reduce accidental marine species capture (iii) utilizing physical barriers to prevent marine organisms from entering the intake area (Kress et al., 2020; Ladewig and Asquith, 2011; Kress, 2019).

3.4. Plant construction and social impact

Construction and installation of a desalination plant are typically accompanied by the simultaneous construction of pretreatment/post-treatment, intake and outfall facilities. Both previous activities and the construction of internal roads, electricity and sewerage networks can have environmental consequences. Constructing these buildings can cause fumes and dust emissions, noise pollution, damage to bird habitats, mammals, fish, and flora. Taking into account that the construction procedure may take up to 2 years up to the first operation of the desalination plant, the impact may be significant (Wetterau, 2011; Olabarria, 2015). One of the main environmental impacts associated with the plant's construction is the building of marine outfalls. These produce an increase in turbidity, destruction of habitats, among others (see Section 3.1).

With respect to land footprint, the requirements of footprint are variable for different technologies. In particular, the area required is 3.5–5.5 $m^2/(m^3/hr_{installed})$ for SWRO, 4.5–5 $m^2/(m^3/hr_{installed})$ for MSF and 4.5–7 $m^2/(m^3/hr_{installed})$ for MED. Constructing an SWRO plant therefore needs slightly less land than constructing MED/MSF plants. However, variances on the value of the required area occur in all cases. This can be due to the fact that the pretreatment facilities rely on the quality of the feed water and therefore pretreatment may be minimal in some cases and, in other cases, pretreatment may be extensive, resulting in an analogous space requirement (Arafat, 2017; Boden and Subban, 2018). It is important to note that first-generation plants were not built to minimize the requirements for footprint and this led to high footprint requirements. However, there is a goal in recent years of minimizing the land footprint and achieving minimal land alteration (Al-Gobaisi, 2010; Gude, 2018). Concerning the social impact, RO plants have wider acceptance than thermal-based plants (MED and MSF) due to their lower energy consumption and lower GHGs emissions, as discussed previously in Section 3.2. Thermal-based plants, however, are more commonly used in regions like the Middle East where energy costs are low, and are the same acceptable as RO plants. The integration of RES into thermal plants is a step that makes thermal plants more socially acceptable (Gude, 2018; Panagopoulos, 2020a; Haddad et al., 2018).

Furthermore, the construction of desalination plants in uninhabited areas leads to human resettlements. A new desalination plant will provide the local community with new employment prospects, as well as the people who would be moved there. Fishing activity can be affected only when proper mitigation measures are not adopted for brine discharge management from an RO or thermal-based plant. As a consequence, this may lead to the unemployment of local fishermen (Arafat, 2017). In the case of well-designed marine infrastructures, however, as reported in recent studies, a higher number of fish have been found in the discharge areas. In particular, Kelaher et al. (2020) studied the effect of desalination reject on the abundance of reef fish and their diversity at Sydney Desalination RO Plant (Australia). The researchers found that a 279% increase in the number of fish in the outlet sites was achieved from before to after discharge began. To this end, several measures should be taken during the construction of the plant to avoid any adverse impact. Measures to be taken are as follows: (i) minimizing the length and number of electricity and water lines (ii) taking advantage of those areas where water and energy supply lines already exist, such as thermoelectric, hydropower ports, etc. (iii) identifying the appropriate location for the plant, ensuring that its impact on economic and outdoor activities is minimal (iv) informing the local people about easier access to freshwater and job creation.

Table 5
Summary of mitigation measures and future prospects for reducing the environmental impacts of desalination and brine treatment.

Impacts	Mitigation measures and future prospects
Brine discharge	- Near-field and far-field modeling approaches - Environmental monitoring plans (EMPs) - Dilution with cooling water from power plants - Zero Liquid Discharge (ZLD) - Minimal Liquid Discharge (MLD) - Resource recovery (Brine mining)
Energy consumption	- Co-generation power-desalination plants - Efficient energy usage plan - Energy recovery devices
GHGs emissions	- Renewable Energy Sources - Waste heat from industrial processes
Chemicals	- Novel green antiscalants - Novel green corrosion inhibitors
Feed water intake	- Multiport diffusers - More corrosion-resistant metallic materials - Locating intake areas with minimal impact - Low speeds in the intake channels

4. Conclusion and future perspectives

Desalination is a valuable process for freshwater recovery since people in many parts of the world depend on it for their daily water needs. At the same time, significant development of new desalination technologies has occurred in the last decade that can treat brine to recover both more freshwater and useful resources. Desalination does have various environmental impacts: brine discharge, high energy consumption, GHGs emissions, intensive use of chemicals and water intake activities. The two most significant impacts are the rejected brine and high energy consumption. Brine has a direct impact on the marine ecosystem and actions are required to address it. Such measures include the adoption of EIA strategies and EMPs, the implementation of near-field and far-field modeling approaches to predict the discharged brine's diffusion and mixing behavior, the adoption of advanced multiple diffusers, the large-scale dilution of the brine before disposal, the concentration of brine at higher concentrations to obtain higher volumes of freshwater and useful resources., etc. Useful resources, namely freshwater and solid salts, are recovered through treatment which can bring substantial financial gains and make desalination more sustainable. Nonetheless, energy consumption is a significant issue, despite significant reductions in the energy requirements of seawater desalination over the last decades. Energy consumption increases with increasing salinity and more than one technology is required to treat the brine, making the utilization of the brine very energy-intensive. At the same time, fossil fuels are primarily used in energy production, which results in the emissions of GHGs and other air pollutants. It is recommended to use renewable energy sources or waste heat from industrial processes to deal with the energy consumption that is inextricably linked to GHGs emissions. It is worth noting that every renewable energy sources are not always available for each location and should be selected appropriately. LCA studies have demonstrated a significant reduction in GHGs emissions at desalination plants powered by renewable energy sources. Environmental concerns also stem from the intensive use of chemicals at various desalination stages. The use of green antiscalants and green corrosion inhibitors is capable of reducing environmentally toxic chemicals. Furthermore, a new desalination plant must be built in areas where neither the ecosystem nor human activities are disrupted. Overall, the measures for addressing desalination's environmental impacts are illustrated in Table 5. Further studies on different aspects of desalination, such as membrane manufacturing, advanced designs, MLD/ZLD systems, diffusers and intake systems, brine mining schemes, etc., should be carried out to resolve the adverse environmental impacts. In addition, future LCA studies regarding new technologies that can treat brine should be performed.

Declaration of competing 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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