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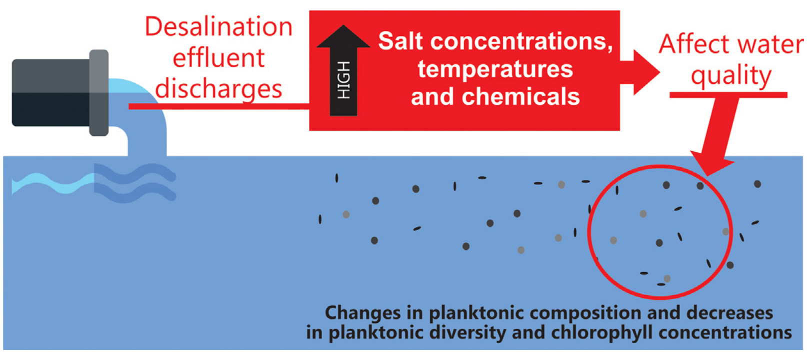
Discussion

Impacts of desalination discharges on phytoplankton and zooplankton: Perspectives on current knowledge

Pedro Henrique Gomes[a,*], Silvano Porto Pereira[b,d], Tallita Cruz Lopes Tavares[a], Tatiane Martins Garcia[a], Marcelo O. Soares[a,c]

[a] Instituto de Ciências do Mar (LABOMAR), Universidade Federal do Ceará (UFC), Abolição Avenue 3207, Fortaleza, Brazil
[b] Companhia de Água e Esgoto do Ceará (CAGECE), Fortaleza, Brazil
[c] Reef Systems Group, Leibniz Center for Tropical Marine Research (ZMT), Bremen, Germany
[d] University of Alicante

GRAPHICAL ABSTRACT



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ABSTRACT

Large-scale application of desalination technology can result in impacts to the marine biota, such as phytoplankton and zooplankton, basal components of marine trophic webs. In this context, our perspective aimed to summarize the impacts of effluent discharges from desalination plants on phytoplankton and zooplankton in order to identify the main gaps and challenges in this theme, propose solutions, and provide recommendations for future work. We identified two main approaches to assess the desalination impacts: laboratory experiments and field studies. Most of these studies were conducted in areas impacted by effluent discharges using the BACI (before, after, and control-impact) approach. They primarily aimed to set out the impacts of hypersaline brine on the surrounding environment and, to a lesser extent, the high-temperature effluents and contaminants from desalination plants. Moreover, phytoplankton was more sensitive to effluent discharges than zooplankton. The main changes observed were a decrease in primary productivity, a loss in diversity, and a change in the community structure of planktonic populations due to the dominance of saline-tolerant groups, which highlights the importance improving treatment or dilution of effluent discharges to minimize the impacts over whole neritic trophic webs, which depend on phytoplankton. From the impacts related to effluent discharges analyzed herein, RO technology was related to most cases of negative impact related to salinity modifications. However, coagulants were related to negative effects in all study cases. Future work should focus on escalate the impacts of such effluents on other trophic levels that could be directly or indirectly

* Corresponding author.
E-mail address: pedrohenriqueg059@gmail.com (P.H. Gomes).

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impacted as well as on how to improve the quality of effluent discharges. Also, we highlight the importance of further baseline and long-term monitoring studies to investigate desalination-induced changes and community resilience to these impacts, as well as studies to provide alternatives to the use of toxic chemicals in the pre-treatment phases.

1. Introduction

The demand for water for human consumption grows every year as this finite resource becomes increasingly scarce owing to overexploitation, water quality impacts, and climate change effects (e.g., droughts and global warming) (UNESCO, 2020). Indeed, water scarcity is one of the most serious problems of our time as it is expected that two-thirds of the World's population will live in water-stressed countries by 2025. In this context, the implementation of desalination technology represents an alternative means to supply ample and safe drinking water to populations living in water-stressed regions (Elimelech and Phillip, 2011a, 2011b). However, as far as the search for technological solutions to water shortages rises so does the knowledge on the impacts of large-scale application of desalination technologies on the marine biota (Jones et al., 2019; Sharifinia et al., 2019). Plankton, as a basal biotic components of marine trophic webs (Montemezzani et al., 2015; Boersma et al., 2008), stands out on this issue as directly exposed to potential hazardous effluent and as a suitable set of model organisms to infer on the potential negative impacts of the operation of desalination plants (Roberts et al., 2010; Belkin et al., 2017). Therefore, the need to understand the impacts associated with the proliferating utilization of desalination technologies is a key issue for sustainable coastal zone development (Le Quesne et al., 2021).

In this review, we summarize the main technologies used in seawater desalination plants along with the characteristics of the effluents produced and methods of discharge, and the potential impacts on phytoplankton and zooplankton. Many reviews have been published on environmental impacts of desalination but most of them do not include any reference to the impacts on planktonic communities. In this regard, we focused our review on impacts on phytoplankton and zooplankton. Based on this, we identified gaps and challenges for the safe implementation of desalination plants focused on minimizing impacts. Also, based on the increasing importance of desalination technologies in a water-stressed planet, as projected by climate change and global temperature projections, we provide recommendations and suggestions for future research on this theme.

Table 1
Advantages and disadvantages of reverse osmosis (RO) and thermal distillation (TD) technologies for seawater desalination (adapted from Sharifinia et al., 2019).

Desalination technology	Advantages	Disadvantages
Reverse osmosis (RO)	Easy adaptation to the implantation site.	Membrane colmatation.
	The plant can be adjusted to meet higher demand after implementation.	Complex configuration.
	Lower financial cost than thermal plants.	Specialized manpower for operation and maintenance.
	Higher conversion efficiency for potable water	Increased use of chemicals during the process
Thermal distillation (TD) (MED/MSF)	Easy management and maintenance.	High power consumption.
	Suitable for switching with renewable energy from intermittent sources.	It needs antifouling agents to prevent fouling on the evaporating surface.
	Less use of chemicals when compared to RO	Cannot operate below 60 % of capacity.
		Low conversion efficiency for potable water

2. Seawater desalination technologies and their effluent discharges

Currently, reverse osmosis (RO) and thermal distillation (TD) (subdivided into multi-stage flash and multi-effect distillation) processes are among the most widely used desalination technologies (Ihsanullah et al., 2021). In RO, the saline water travels through a pre-treatment system before it reaches the RO membranes. Thereafter, high-pressure water flows through semi-permeable membranes, initiating the separation process between water and salts (Semiat, 2000). In the TD process, seawater is heated in evaporation chambers, changing it from a liquid into a gaseous state via evaporation. Thereafter, evaporated water is reverted to its original liquid state via condensation, producing a water stream with a very low salt concentration (i.e., product stream) and another with a high salt concentration (i.e., brine stream) (Nassrullah et al., 2020). Desalination plants operate across all continents, and there are strong growth prospects for this activity in the coming years (Moossa et al., 2022), with emphasis on RO technologies. Currently, the largest number of desalination plants are in the Middle East, followed by North America, Asia, Europe, Africa, Central America, and South America (Sharifinia et al., 2019). Both TD and RO technologies have advantages and disadvantages (Table 1).

Initially, the use of TD processes was widespread, mainly in arid Persian Gulf countries. However, due to the high consumption of thermal and electric energies along with the large emissions of greenhouse gases, RO membrane technology has since gained prominence and is more widely used today (Greenlee et al., 2009; Lim et al., 2021). With a higher energy-efficiency, RO contributes with 62 % of global desalinated water production (Sharifinia et al., 2019). Nevertheless, technologies for seawater desalination continues to improve aiming at better energy efficiency and environmental sustainability. Both technologies can lead to disturbances in plankton communities, which can include the release of effluents with high temperatures or salinity (Roberts et al., 2010).

The physical and chemical compositions and concentration levels of these effluents can vary depending on the technology used, as well as others factors like feed water quality, pretreatment processes used, chemicals added (e.g., antiscalants, acids and chlorine), process configuration (recovery) and operational constraints. In general, effluents are composed of high salt concentrations (up to 80 g/l), high temperatures (up to 20 °C above the ambient environment for TD discharges), no or low dissolved oxygen content (for TD discharges), and by the presence of chemical waste. Moreover, they can release various heavy metal into effluent waste streams, depending on the type and quality of metallic alloys used in the desalination plants or whether metal-based scale inhibitors were used (Le Quesne et al., 2021; Sharifinia et al., 2022; Lettemann and Höpner, 2008). In addition, to avoid fouling, corrosion, and clogging in desalination systems, it is necessary to use chemicals (e.g., antifouling agents, biocides, and coagulants) that minimize these impacts on the operation of the plants. These antifouling agents can also increase nitrogen and phosphorus concentrations in water (Ihsanullah et al., 2021).

3. Treatment approaches for desalination plants effluents

The concentration levels of effluent discharges of different seawater desalination techniques can maximize or minimize environmental impacts. For instance, RO plants can release brine that is more saline than TD plants (Khan and Al-Ghouti, 2021). Those characteristics are important for assessing the ecotoxicological effects on marine biodiversity, which includes plankton species (Portillo et al., 2014a, 2014b). This explains the necessity of developing alternatives and treatment for such effluents.

The environmental impacts attributed to the discharges of TD plants are similar to that of RO, and in both processes it is possible to verify residues of chemical compounds used in the pre-treatment of the feed water (Panagopoulos et al., 2019). However, TD's effluents can generate a greater impact on the environment because of the high temperature (up to twice the ambient value) and, in addition, the volume of the effluent generated is up to five times higher than in RO, due to the low efficiency in the water purification process, causing a greater release of tailings and also by the disposal of water used for cooling the plant (Elsaid et al., 2020; Soliman et al., 2021a). Despite those differences, both technologies discharge their effluents into the ocean after desalination, with salinity and temperature being the main properties that differ between the two processes, which causes differences in the effluent density as the higher the salinity, the higher the density; the higher the temperature, the lower the density (Bleninger and Jirka, 2010).

Many RO desalination plants employ segregation, neutralization, or treatment methods on their process waste streams prior to their discharge of effluent into the ocean. In addition, the effluent discharges from these plants into the ocean generally occur via submarine outfalls that have diffuser structures, which are designed to allow for the rapid dilution of effluent contents within a localized marine area (Missimer and Maliva, 2018; Voutchkov, 2011). In the absence of submarine outfalls or favorable conditions to achieve adequate dilution, some plants can utilize part of their stored seawater to dilute their effluent prior to discharge (Shrivastava and Adams, 2019). Such strategies can significantly reduce impacts on marine biota such as zooplankton and phytoplankton (Fig. 1).

Desalination plant discharges that have high chemical concentrations, temperatures, and salt concentrations can alter the environmental parameters of the receiving water body and damage the abundance, diversity, metabolic rates, and physiological processes of marine biota (Alharbi et al., 2012; Sadiq, 2002; Sanni and Popoola, 2019). These factors (high temperature, high salinity, and chemical compounds) can jointly alter the biodiversity of regions near plant discharges, and some species may respond negatively to the effluent discharged from desalination processes (Sharifinia et al., 2019).

Disposal method is also important since it affects the impact produced by desalination effluents (Fernández-Torquemada et al., 2019). Direct disposal produces higher impacts than disposals that favor the dilution of the effluent (Belatoui et al., 2017). Diffusers or seawater by-passing have proved effective to increase the dilution and to reduce the impacts of the discharges (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2009; Loya-Fernández et al., 2012, 2018; Sola et al., 2020).

4. Potential impacts on marine phytoplankton and zooplankton

Some marine organisms are susceptible to effluent discharges from desalination plants, such as epifauna, seagrass, and phytoplankton, for which decreases in diversity and growth rates have been reported (Roberts et al., 2010; Fernández-Torquemada et al., 2005; Gacia et al., 2007; Belkin et al., 2017). However, plankton are one of the most important, though understudied, groups regarding the impacts of desalination plants, which highlights the need for studies that synthesize our current knowledge on this topic. Given the strong growth prospects in the number of desalination plants in the near term (Moossa et al., 2022) and their associated ecological impacts (Soliman et al., 2021a, 2021b), further research is needed to mitigate their impacts on marine plankton biodiversity. However, this topic has not been reviewed (Supplementary Material I) in the literature to date. In this context, our perspective aimed to summarize the impacts of effluent discharges from desalination plants on phytoplankton and zooplankton.

Both phytoplankton and zooplankton are important components of the marine plankton community structure, as they form the basis of marine food webs (Mohr and Kiørboe, 2018). In this context, phytoplankton synthesizes organic matter from inorganic sources, and zooplankton herbivory assists in the transfer of energy to higher trophic levels in coastal ecosystems (Gaedke, 2009). When considering the entire aquatic food web, phytoplankton and zooplankton communities are closely connected (Boersma et al., 2008). Moreover, these organisms are vital to nutrient cycling in coastal environments as they play key roles in the biogeochemical cycles of the planet (Sánchez-Baracaldo et al., 2022; Montagnes and Fenton, 2012). These organisms are mostly small and have an extremely short life cycle; therefore, they respond quickly to environmental changes. These characteristics make them excellent biological indicators and models (Garzon-Garcia et al., 2018) for assessing the environmental effects of effluent discharges from desalination plants.

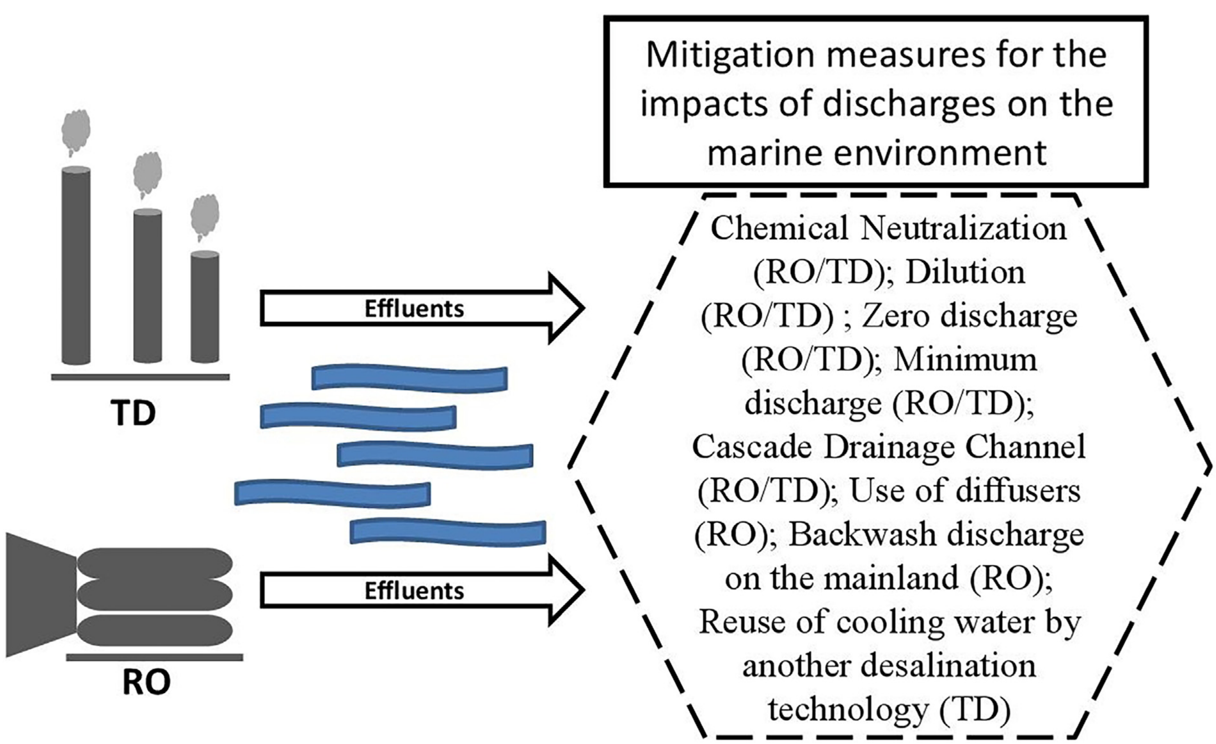

Fig. 1. Measures to mitigate the impacts of effluents practiced in the TD and OR plants.

4.1. Impacts related to effluent discharges from desalination plants

Most studies have been done with phytoplankton (59 %) compared to zooplankton (41 %) and among them, field studies (62 %) are the majority compared to laboratory research (38 %). In addition, most of them focused on the impacts of high salinity compared to high temperature (14 %) and contaminant discharge (21 %) (Fig. 2). The impacts of desalination plants include the construction of plants in the coastal zone, air pollution, and the entrainment of marine biota (Lee and Jepson, 2021). However, the main impacts of desalination plants on the marine environment are related to their effluent discharges. These discharges have high salt concentrations and temperatures and contain various chemicals that can adversely affect water quality, planktonic diversity, and coastal ecosystem stability (Le Quesne et al., 2021; Belkin et al., 2017) (Table 2).

Several studies have described impacts on plankton, such as changes in planktonic composition and decreases in planktonic diversity and chlorophyll concentrations (Belkin et al., 2017; Drami et al., 2011). Among them, field studies have shown that phytoplankton communities are more susceptible to these changes than zooplankton (Yoon and Park, 2011; Grossowicz et al., 2021). However, some studies have reported little or no negative impacts on planktonic communities when exposed to brine discharge activity (Abdul-Aziz et al., 2003; Ozair et al., 2017; Saeed et al., 2019), which will be discussed along this section (Table 3).

4.2. Thermal discharges

Discharges of high temperature mainly originate from thermal desalination plants, which release thermal discharges to the marine environment after the seawater heating process (Le Quesne et al., 2021). The intensification of thermal desalination discharges can harm marine biota, cause changes in species composition and abundance, and reduce biodiversity at discharge sites (Lettemann and Höpner, 2008; Chang, 2015). There is evidence that rising water temperature scan cause harm to marine organisms, and more specifically to plankton. Mabrook (1994) reported the disappearance of planktonic organisms near desalination plant discharge points in the Red Sea region (Δ 4.5 °C); however, no details were provided on this impact caused by the effluent. The author further suggests an adjustment of the discharge water temperature to approach ambient (Red Sea) levels.

However, studies in a region of the Persian Gulf affected by desalination plant activity reported that although there was a difference of approximately 8 °C between the water intake and effluent discharge points, there were no major impacts on phytoplankton density and no change in the overall composition of planktonic species (Abdul-Azis et al., 2003; Saeed et al., 2019) (Table 4). The minimal impact observed on this plankton community may be explained by the resistance of the local biota to high temperatures, as the Persian Gulf region is historically known to have the highest recorded marine surface temperatures in the world (Alosairi et al., 2020).

4.3. Brine

Excessive salt concentrations generate osmotic stress in organisms, which causes dehydration in cells from a decrease in turgor pressure. This can lead to the death of some plankton species (Belkin et al., 2015; Garrote-Moreno et al., 2014). The density of brine tends to be higher than that of seawater, indicating that brine can be deposited in benthic environments (Sola et al., 2019). Consequently, benthic communities (i.e., seagrass beds, communities of unconsolidated bottoms, and reefs) tend to be more affected (Frank et al., 2017; Petersen et al., 2018a, 2018b). Brine impacts on plankton may be intensified in sheltered and shallow environments (e.g., bays) than in open coasts with intense hydrodynamic regimes created by waves, tides, and currents (Lettemann and Höpner, 2008). The effects of brine from desalination plants on marine planktonic organisms varied; some groups were more sensitive than others (Table 5).

4.3.1. Laboratory investigations

Laboratory studies tested salinity values usually observed in discharges from desalination plants (38–90 ppt). Yoon and Park (2011) observed that phytoplankton species *Isochrysis galbana* suffered 50 % inhibition of population growth at 42.2 ppt salinity, whereas *Chlorella vulgaris* was more tolerant, with growth inhibition at 61.7 ppt salinity (Yoon and Park, 2011). The authors also reported a lower sensitivity for zooplankton species (rotifers

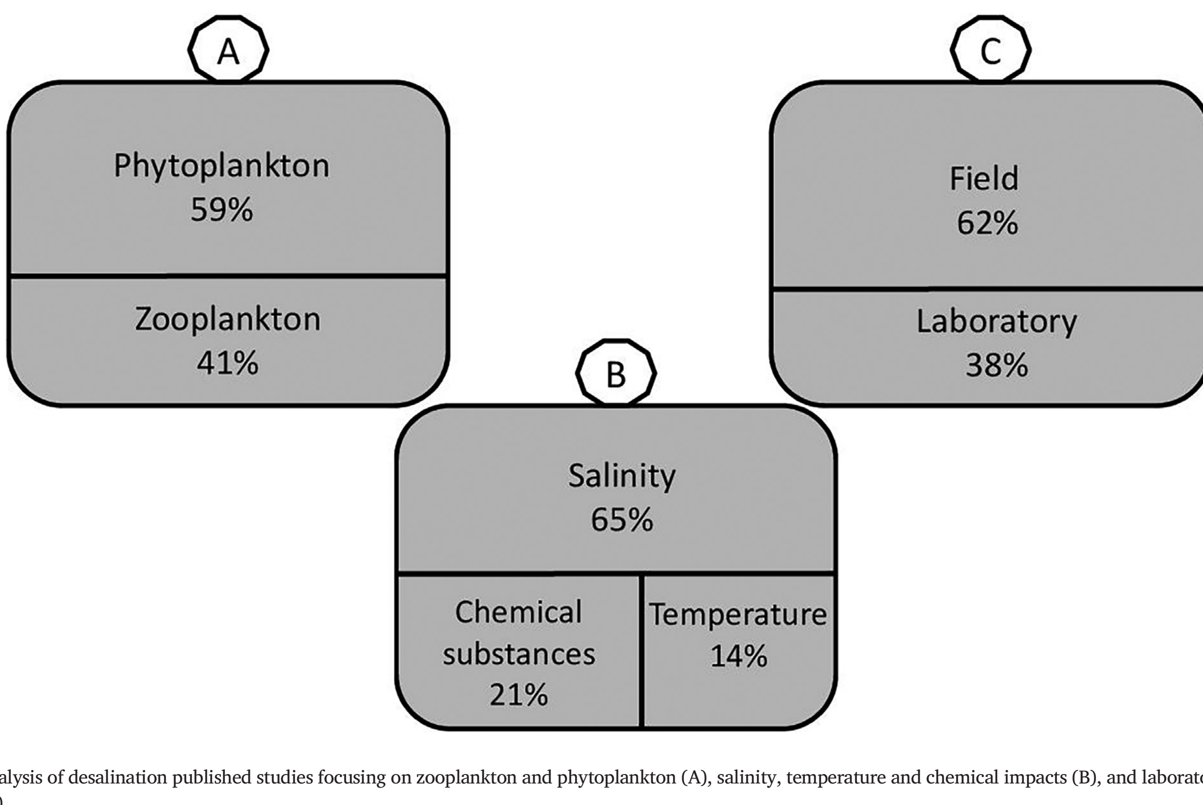

Fig. 2. Analysis of desalination published studies focusing on zooplankton and phytoplankton (A), salinity, temperature and chemical impacts (B), and laboratory and field studies (C).

Table 2
General characteristics of effluents from MSF/MED e RO.

Parameters	MSF/MED	RO
Temperature	Brine: 3–25 °C above ambient; combined: ~5–20 °C above ambient	If subsurface intakes: may be below ambient T due to a lower T of source; If open intakes used: close to ambient; If mixed with cooling water of power plants: may be above ambient
Salinity (g/l) (depending on ambient salinity and recovery rate)	Brine: 60–70; Combined: 45–60	65–85 g/l
Biocide (chlorine)	0.2–0.45 ppm, both brine and cooling water contain residual chlorine	Neutralized with sodium bisulfite to prevent membrane damage
Trihalomenthane (THMs)	Can form during chlorination, but at low concentrations	Can form during chlorination, but at low concentrations
Antifouling (donations applied)	4–6 ppm	2 ppm
Flocculants/coagulants	Not usually used for thermal processes	Coagulants dosage between 1 and 30 mg/l (often iron III salts); Coagulant aids dosage between (0.1 and 5 mg/l)
Heavy metals	Metallic equipment made from carbon steel, stainless steel, aluminum and aluminum brass, titanium, or copper nickel alloys; Concentrate may contain iron and copper, copper levels can be an environmental concern; No data on brine contamination available	Metallic equipment made from corrosion-resistant stainless steel; Concentrate may contain low levels of iron, chromium, nickel, molybdenum if low-quality steel is used
Total dissolved solids (TDS) mg/L	≤70	≤70
Cleaning chemicals (used intermittently and only present if cleaning solutions are discharged to surface waters)	Acidic (pH 2) washing solution which may containing corrosion inhibitors such as benzotriazole derivates	Alkaline (pH 11–12) or acidic (pH 2–3) Solutions with additives such as: detergents (e.g. dodecylsulfate), complexing agents (e.g. EDTA), oxidants (e.g. sodium perborate), biocides (e.g. formaldehyde)

Brachionus plicatilis and a benthic copepod *Tigriopus japonicus*) than for phytoplankton species, and these organisms experienced 50 % mortality of the population above 65 ppt salinity (Yoon and Park, 2011). In general, 40 ppt salinity appeared to be the threshold concentration for acute brine toxicity in the planktonic organisms evaluated (Yoon and Park, 2011).

In laboratory experiments performed at different salinities (5 % and 15 % higher than environment) with a community of phytoplankton, an acute decline in chlorophyll concentration (most intense at a 15 % increase) was observed, suggesting immediate (within 2 h) salt stress for the algal biomass. Subsequently, for the duration of the experiments (11–12 days), chlorophyll and primary productivity rates increased 2×–5× and 1.5×–2.5× relative to the control, respectively. However, this increase in productivity was coupled with a change in organism composition (Belkin et al., 2015), indicating the adaptive capacity of some phytoplankton groups exposed to brine (under laboratory conditions).

Laboratory tests with three key phytoplankton species (*I. galbana*, *T. suecica*, and *C. vulgaris*) and two zooplankton species (rotifers *B. plicatilis* and a benthic copepod *T. japonicus*) revealed no significant acute differences in the planktonic organisms evaluated, although there was a salinity difference of approximately 40 % between the discharged water and the control (natural seawater) (Park et al., 2011). The aim of these analyses was to verify the toxicity of brine discharge from an RO plant. This result contradicts that reported by Belkin et al. (2015), who identified an acute impact on phytoplankton by applying lower thresholds in salinity differences (5 %–15 % between samples). However, the assessment methods employed in these studies differed, making it difficult to compare the results directly. Belkin et al. (2017) reported, from field surveys, that phytoplankton communities near the brine discharge point (5 % salinity increase above ambient conditions) were characterized by lower diversity when compared to communities in the natural environment without impact. In addition, there was a change in plankton composition between affected and unaffected areas. However, it was not determined whether these changes were due to altered salinity or effluent properties, including the presence of coagulants and antifouling agents (Belkin et al., 2017).

4.3.2. Data from real desalination plants

In a region of the Red Sea near a desalination plant discharge, the phytoplankton community showed little variation, and the overall species composition was not affected by brine discharge. Although there was an initial slight drop in phytoplankton density at the site following effluent discharge, rapid recovery was noted at adjacent sites (Ozair et al., 2017). This recovery may have reflected the mixing and dilution of the brine discharge by a large volume of water. In addition, there is intense ocean current circulation in this region, which facilitates the dilution and dispersion of brine discharges (Ozair et al., 2017).

Studies in the Mediterranean Sea have not identified negative impacts regarding brine discharges on planktonic communities. They have also not revealed spatial changes in phytoplankton and zooplankton structures, suggesting that the trophic structures of plankton were not significantly altered between brine discharge points and non-impacted areas (Grossowicz et al., 2019). In another study, no significant differences were observed in the composition and abundance of zooplankton community exposed to impacts from brine discharge (Grossowicz et al., 2021).

Saeed et al. (2019) used chlorophyll concentration and phytoplankton density as parameters to assess the impacts of desalination plants on phytoplankton communities. The authors reported that there were significant increases in phytoplankton densities and chlorophyll concentrations at the effluent discharge point of a plant in Jeddah (Red Sea) when compared to measurements at the intake point (mean difference in salinity between discharge and intake points was 0.6 ppt). On the other side, for the Haql plant (also in the Red Sea), there were no significant differences observed in phytoplankton densities and chlorophyll concentrations between the discharge and intake points (mean salinity differences of xx ppt). According to the authors, these results justify the minimal impacts of brine discharges on the phytoplankton communities owing to the rapid dilution of brine and the subsequent slight changes to the salinity of the receiving coastal body (Saeed et al., 2019). However, it is recommended to emphasize that increases in chlorophyll densities and phytoplankton concentrations viewed in isolation do not constitute a positive change in the environment, as increases in these parameters can also indicate negative impacts, such as localized marine eutrophication (UNESCO, 2017).

4.4. Chemical contaminants

The chemical composition of the effluent results in major impacts on plankton community development and distribution (Kumar et al., 2022; Caroppo, 2000). A number of chemicals can be used in desalination plants, including oxidizing (e.g., hydrogen peroxide and chlorine) or non-oxidizing (e.g., formaldehyde and glutaraldehyde) biocides (Lettemann and Höpner, 2008), alkaline solutions (pH 11–12), acidic solutions (pH 2–3), polyphosphates, phosphonates, aluminum hydroxide, aluminum sulfate, ferric chloride, and polyacrylamide (Belkin et al., 2017; Sadhwani et al., 2005; Lettemann and Höpner, 2008). These compounds are employed to remove metal oxides, scales, and biofilms (Chang, 2015) and combat the coagulation of suspended particles in water (Sadhwani et al., 2005). Hot acids are also used to clean alkaline scales (Ihsanullah et al., 2021). These chemicals and solutions with extreme pH values (high or low) can harm marine organisms if not properly neutralized, resulting in negative impacts on the marine ecosystem (Sadhwani et al., 2005; Portillo et al., 2014a,

Table 3
Field and laboratory surveys on the ecological impacts of desalination effluent discharges on phytoplankton and zooplankton Summary of relevant aspects of the studies selected for this perspective. Symbol code indicates negative (−), neutral/no (0) or positive impact (+) observed during the studies.

Desalination/discharge technology	Research type	Location/region	Relevant aspects of the studies	Impacts	References
RO/co-discharged directly at shoreline	Field	Mediterranean Sea	The trophic structure of the plankton did not change significantly between the point of brine discharge and the point outside the influence of that discharge.	0	Grossowicz et al. (2019)
RO/co-discharged directly at shoreline	Field/laboratory	Mediterranean Sea	Altered phytoplankton composition and low phytoplankton diversity near the brine discharge point (Field). Iron hydroxide (1 mg Fe/L) significantly decreased the abundance and altered the phytoplankton community (laboratory).	–	Belkin et al. (2017)
RO/submarine outfall	Laboratory	Mediterranean Sea-Israel	A 15 % difference in salinity caused an acute decline in chlorophyll concentration, leading to a decrease in algal biomass.	–	Belkin et al. (2015)
RO/co-discharged directly at shoreline	Field	Mediterranean Sea	Backwash discharge containing iron hydroxide caused a decrease in phytoplankton density.	–	Drami et al. (2011)
RO and TD/submarine outfall and directly at shoreline	Field	Persian Gulf and Red Sea	Higher phytoplankton density and chlorophyll concentration at the effluent discharge point of the plant.	+	Saeed et al. (2019)
RO and TD/directly at shoreline	Field	Red Sea	The phytoplankton populations showed no major variations, and the overall species composition was not affected by the brine discharge.	0	Ozair et al. (2017)
TD	Field	Red Sea	Many planktonic organisms have disappeared from the area near the desalination plant.	–	Mabrook (1994)
RO/directly at shoreline; co-discharged directly at shoreline	Field	Red Sea	There was no significant difference ($p > 0.05$) in zooplankton community composition and abundance between the brine discharge sites and the points outside of that influence.	0	Grossowicz et al. (2021)
RO and TD/directly at shoreline	Field	Persian Gulf	The overall species composition of the plankton was not affected by the discharge from the desalination plant.	0	Abdul-Azis et al. (2003)
RO and TD/directly at shoreline	Laboratory	Jubail-Saudi Arabia	The adult copepods and larval stages were relatively tolerant to the residual chlorine concentrations used in the tests (0.2, 0.5, 0.8, and 1.0 mg Cl/L).	0	Ershath et al. (2019)
RO	Laboratory	Incheon-South Korea	Population growth of three species (*Skeletonema costatum, Tetraselmis suecica* and *Isochrysis galbana*) of phytoplankton decreased markedly at concentrations above 45 ppt salt. Zooplankton had lower sensitivity to brine (above 65 ppt).	–	Yoon and Park (2011)
RO	Laboratory	Incheon-South Korea	The tests showed no significant acute differences for the planktonic organisms assessed, although there was a difference in salinity of approximately 40 % between the discharge water and the control (natural seawater).	0	Park et al. (2011)

Table 4
Temperature values and effect on plankton species/communities.

References	Location/region	Temperature difference (°C)	Effect	Species/community
Saeed et al. (2019)	Persian Gulf	21.5 ± 5.5–28.5 ± 7.5	Discrete increase in density	Phytoplankton
Abdul-Azis et al. (2003)	Persian Gulf	25.5 ± 6.5–34.3 ± 4.7	No major changes in plankton structure	Phytoplankton/zooplankton
Mabrook (1994)	Red Sea	23–27.5	Disappearance of organisms	Plankton

2014b). In this section, we provide an overview of the impacts of contaminants from desalination plant discharges on plankton.

4.4.1. Biocide (chlorine)

Chlorine is a widely used biocide in desalination plants (Lettemann and Höpner, 2008). The addition of chlorine to the water used for desalination forms hypochlorite and other byproducts that can be released into the receiving environment when discharged. It was suggested that between 10 % and 25 % of the total chlorine concentration (free chlorine + combined chlorine) from this initial addition is ultimately released as part of the discharge to the marine environment (Dawoud, 2012). This phenomenon is limited to TD plants, as RO plants neutralize chlorine compounds before the water comes into contact with the filtration membranes (Kavitha et al., 2019). Chlorine has an ecotoxicological effect on marine life, and

Table 5
Salinity values and effect on plankton species/communities.

References	Location	Salinity	Effect	Species/community
Yoon and Park (2011)	Laboratory	42.2–61.7 ppt	50 % inhibition of population growth.	*Skeletonema costatum*, *Chlorella vulgaris*, *Tetraselmis suecica*, *Isochrysis galbana*.
		>65 ppt	50 % mortality.	*Brachionus plicatilis*, *Tigriopus japonicus*.
Belkin et al. (2015)	Laboratory	38.8–44.62 ppt (spring) 39.3–45.5 ppt (summer)	Acute decline in algal biomass.	Phytoplankton
Belkin et al. (2017)	Mediterranean Sea	39.0–41.0 ppt (winter) 39.6–41.6 ppt (summer)	Decrease in diversity.	Phytoplankton
Park et al. (2011)	Laboratory	33–45 ppt	No significant effect.	*Isochrysis galbana*, *Tetraselmis suecica*, *Chlorella vulgaris*, *Brachionus plicatilis*, *Tigriopus japonicus*.
Grossowicz et al. (2019)	Mediterranean Sea	Not specified	There were no significant impacts.	Plankton
Grossowicz et al. (2021)	Mediterranean Sea	Not specified	There were no significant impacts.	Zooplankton
Ozair et al. (2017)	Red Sea	Not specified	Small decrease in density at the discharge point, with rapid recovery in adjacent regions.	Phytoplankton
Saeed et al. (2019)	Jeddah-Red Sea	39.3–39.9 ppt	Increase in density.	Phytoplankton
	Haql-Red Sea	Not specified	No significant changes in density.	

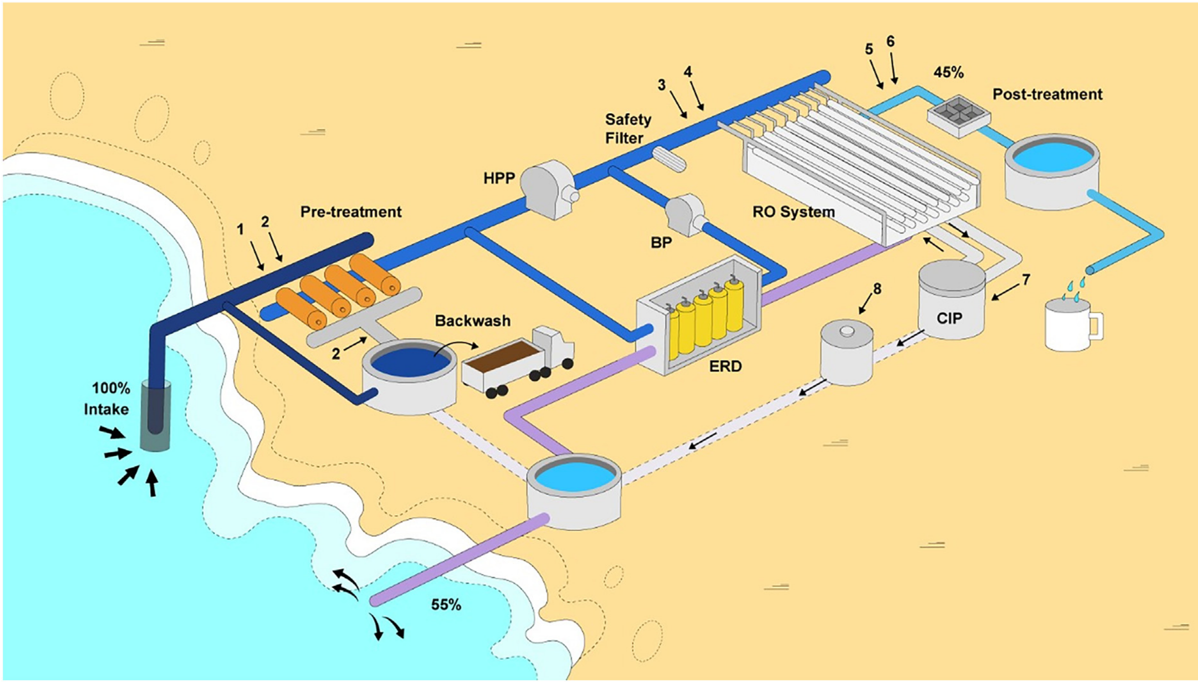

Fig. 3. Typical arrangement of a SWRO desalination process. Biocides (1) and coagulants (2) products are applied on the raw water, whereas dichlorination (3) and antifouling (4) agents are added before the RO membranes. Acid and alkaline products and dichlorination agents (8) are used to neutralize water from CIP process, generated by the membrane chemical cleaning (7). For the backwash water treatment, often are using coagulants products and for post-treatment usually CO_2 and $CaCO_3$. RO: reverse osmosis. HPP: high-pressure pump. BP: booster pump. ERD: energy recovery device. Source: the authors.

although there is degradation and dilution of total chlorine in the marine environment after discharge, environmental risks still exist (Lettemann and Höpner, 2008).

Ershath et al. (2019) studied three species of copepods and nauplii in an ecotoxicological assessment using different concentrations of chlorine (0.2, 0.5, 0.8, and 1.0 mg/l). The copepods consisted of *Paracalanus aculeatus* (Calanoida), *Oithona rigida* (Cyclopoida), and *Euterpina acutifrons* (Harpacticoida). No significant differences between the treatments were observed, except for the mortality of *P. aculeatus* at a concentration of 1.0 mg Cl/l. This concentration (1.0 mgCl/l) is well above that observed in effluent discharges from the Jubail (Persian Gulf) plants, which range between 0.2 and 0.58 mg Cl/l annually. The results of this study suggest that adult copepods and larval stages are relatively tolerant of low residual chlorine concentrations from the desalination plants located on the Jubail coast. However, this topic needs further exploration in other coastal areas around the world.

4.4.2. Coagulants

Coagulants are chemical substances that aid in the filtration of water entering the desalination plant feed systems (Lettemann and Höpner, 2008). These products help aggregate suspended solid particles and transform them into larger particles, thus facilitating their retention in the filtration system. These products include aluminum hydroxide, iron hydroxide, aluminum sulfate, ferric chloride, and polyacrylamide (Belkin et al., 2017; Sadhwani et al., 2005). These substances have low toxicity in aquatic environments (Lewandowska and Kosakowska, 2004; Lettemann and Höpner, 2008), and they are released into the marine environment after the filters are backwashed. Although they are not toxic to the environment, they can affect planktonic communities. For example, backwash discharges containing iron (from iron hydroxide) and particulate matter increased the turbidity of the water, decreased the efficiency of phytoplankton growth (Drami et al., 2011), and induced the aggregation of organisms, which decreases the abundance of plankton and changes the structure of planktonic communities (Belkin et al., 2017).

The use of iron hydroxide (coagulant) was proven to be more deleterious to phytoplankton than the use of polyphosphonates (antifouling agent) or chlorine (biocide) (Drami et al., 2011). A concentration of 1 mg Fe/l (lower than the limit of 2 mg Fe/l allowed for discharges from some desalination plants) caused a significant decrease in the abundance of phytoplankton and altered the composition of phytoplankton communities. This mainly contributed to an increase in diatoms and Chrysophyceae (Belkin et al., 2017). This result was obtained through mesocosm experiments and did not account for the dilution factor at the site of the effluent discharge. Iron hydroxide is a coagulant globally used in desalination plants. Its use, coupled with high salinity and antifouling agents in plant effluent, can cause negative impacts on phytoplankton structures, mainly in those communities in sheltered coasts or those communities with low dilution capacities (Belkin et al., 2017). Drami et al. (2011) reported that backwash discharges from a RO plant modified the color of the water (reddish plume) near the discharge point and attributed this effect to the iron hydroxide (coagulant) used in the desalination plant. In addition to the aesthetic effect, it was found that the efficiency of phytoplankton growth decreased in response to increased turbidity, which hinders the penetration of underwater radiation and thus limits photosynthesis (Drami et al., 2011).

4.4.3. Antifouling agents

Antifouling agents are added to feed water in TD and RO plants to disperse calcium and magnesium ions and thus prevent fouling (Le Quesne et al., 2021). Phosphonates (organophosphonates and polyphosphonates) are the most used antifouling agents. These compounds contain phosphorus, which can enter the coastal environment via effluent discharges (Petersen et al., 2018a, 2018b). Polyphosphates are also used in desalination plants, but to a lesser extent; moreover, they form compounds that are easily hydrolyzed into orthophosphates (Shaikh et al., 2015), which are important nutrients for primary production. In contrast, phosphonates have low biodegradability and thus tend to have longer residence times in aquatic environments (Lettemann and Höpner, 2008). Chang (2015) reported a change to biodiversity as one of the effects related to the use of antifouling agents. Experiments conducted with phosphonate additions (0.2 mg/l) did not induce immediate changes in phytoplankton communities; however, after 10 days, increases in planktonic diversity and diatoms were observed (Belkin et al., 2017). Despite these results, we highlight the lack of field studies in the literature in our review.

4.4.4. Heavy metals

Heavy metals are persistent pollutants that bioaccumulate in marine organisms along the food chain (Machado et al., 2015). These metals can cause a range of impacts on organisms and ecosystems due to their toxicity and persistence in the environment; thus, they are considered important pollutants in marine environments (Ruilian et al., 2008; De Forest et al., 2007). The production of water for human sustenance through desalination practices generates effluent discharges with varying concentrations of heavy metals (Van Der Bruggen et al., 2003). These metals are concentrated in both water columns and marine sediments (Chang, 2015) and can affect marine biota in the receiving environment. The heavy metals found in desalination plant effluents can originate from various sources, such as products to prevent pipe corrosion and antifouling agents (Chang, 2015). Even in the absence of using products to minimize corrosion, heavy metals are still released via corrosion of the metals that make up the pipes. Therefore, these metals are eventually released through effluent discharges into the aquatic environment (Le Quesne et al., 2021).

Heavy metals not only reduce the abundance and diversity of plankton species (Hosono et al., 2011) but also bioaccumulate in aquatic organisms and harm the populations that feed on these contaminated organisms (Sadiq, 2002). Furthermore, these metals can impact phytoplankton and zooplankton community structures (Sathicq and Gómez, 2018; Griboff et al., 2018), leading to changes in the abundance, richness, and diversity of plankton species (Van Regenmortel et al., 2018). The susceptibility of plankton species varies in response to the concentration and properties of the metals. Chakraborty et al. (2010) reported that copper and zinc (at concentrations of 2.5×10^{-6} M) caused mortalities in chlorophytes and cyanobacteria, while nickel and cobalt potentiated chlorophyte biosynthesis at the same concentrations. Although heavy metals are extremely õrelevant to marine ecology because of their toxicity to aquatic organisms, very few studies have been found that examine the impacts of heavy metals in desalination discharges on planktonic communities.

5. Knowledge gaps and recommendations for future research

Future work should focus on escalate the impacts of such effluents on other trophic levels that could be directly or indirectly impacted as well as on how to improve the quality of effluent discharges. Also, we highlight the importance of further baseline and long-term monitoring studies to investigate desalination-induced environmental changes and marine community resilience to these changes, as well as studies to provide alternatives to the use of toxic chemicals in the pre-treatment phases.

From the impacts related to effluent discharges analyzed herein, considering both laboratory and field studies, RO technology (Fig. 3) was related to most cases of negative impact related to salinity modifications. It is worth noting that adverse effects have not been observed in all studies and that there are still a limited number of studies that have evaluated the impacts of discharges on zooplankton and phytoplankton simultaneously. More information is required, especially on the impacts of heavy metals on zooplankton communities. We emphasized the importance of conducting field studies in combination with laboratory investigations to obtain a comprehensive overview of the impacts of effluent discharges from desalination plants on planktonic communities.

6. Conclusions and final considerations

Most published research has focused on the impact of brine discharge on planktonic communities. From the studies evaluated, it could be concluded that phytoplankton were more sensitive to effluent discharges from desalination plants than zooplankton. The main changes were a decrease in primary productivity, a loss in diversity, and changes in the community structure of plankton populations due to the dominance of saline-tolerant groups. These impacts can vary depending on: the characteristics of the plankton species inhabiting the impacted area; degree of dilution promoted by ocean circulation (e.g., tides, currents, and waves) at the discharge site; concentration of salts, chlorine, and other substances in the effluent; and characteristics (i.e., composition and concentration) of the plant effluent that is discharged. The OR discharges have a greater negative potential in the planktonic community and we suggest that there is a dilution of the brines, as well as carrying out a backwash launch on the continent in order to minimize the impacts on these organisms. However, the thermal desalination plants that potentially may have higher impacts on planktonic communities than RO plants (positive buoyancy effluent, chlorine not neutralized, increase of temperature and cupper from the corrosion of heat exchangers). Finally, we highlight the importance of further baseline and long-term monitoring studies to investigate desalination-induced environmental changes and marine community resilience to these changes.

Ethical approval

No animal testing was performed during this study.

Sampling and field studies

The study does not contain sampling material or data from field studies.

CRediT authorship contribution statement

Pedro Henrique Gomes: Conceptualization, Writing – original draft, Writing – review & editing, Methodology, Formal analysis. **Silvano Porto Pereira:** Writing – original draft, Writing – review & editing, Formal analysis. **Tallita Cruz Lopes Tavares:** Writing – original draft, Writing – review & editing, Formal analysis. **Tatiane Martins Garcia:** Writing – original draft, Writing – review & editing, Formal analysis. **Marcelo O. Soares:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Methodology, Supervision.

Data availability

Data will be made available on request.

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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Appendix A. Supplementary data

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