UNIVERSIDADE FEDERAL DO CEARÁ
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS MARINHAS TROPICAIS
INSTITUTO DE CIÊNCIAS DO MAR
DOUTORADO EM CIÊNCIAS MARINHAS TROPICAIS

PEDRO HENRIQUE GOMES

DIAGNOSIS OF PLANKTON BEFORE THE IMPLEMENTATION OF THE LARGEST DESALINATION PLANT IN BRAZIL AND CURRENT GLOBAL IMPACTS.

FORTALEZA
2024

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Tese de Doutorado submetido à Coordenação do Programa de Pós-Graduação em Ciências Marinhas Tropicais do Instituto de Ciências do Mar, da Universidade Federal do Ceará, como requisito para a obtenção do grau de Doutor em Ciências Marinhas Tropicais.

Área de Concentração: Ciência, Tecnologia e Gestão Costeira e Oceânica.

Orientador: Prof. Dr. Marcelo de Oliveira Soares.
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Co-orientadora: Dra. Tatiane Martins Garcia.

FORTALEZA
2024

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

G616d Gomes, Pedro.
Diagnosis of plankton before the implementation of the largest desalination plant in Brazil and current global impacts. / Pedro Gomes. – 2024.
133 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, Instituto de Ciências do Mar, Programa de Pós-Graduação em Ciências Marinhas Tropicais, Fortaleza, 2024.
Orientação: Prof. Dr. Marcelo de Oliveira Soares.
Coorientação: Profa. Dra. Dra. Tallita Cruz Lopes Tavares Normando; Dra. Tatiane Martins Garcia.

1. Dessalinização. 2. Fitoplâncton. 3. Mesozooplâncton. 4. Descarga . 5. Impacto. I. Título.
CDD 551.46

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AGRADECIMENTOS

-Ao programa de pós-graduação em Ciências Marinhas Tropicais (LABOMAR-UFC) e a Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) por disponibilizar uma bolsa estudos durante o período de curso.

-Ao Prof. Dr. Marcelo de Oliveira Soares, pela orientação, incentivo e paciência ao longo desses anos!

-As co-orientadoras Dra. Tallita e Dra. Tatiane, muito obrigado pelo suporte!

-Aos colegas do Laboratório de Plâncton do Instituto de Ciências do Mar - LABOMAR/UFC.

-Ao projeto: Avaliação da variabilidade espaço temporal da qualidade da água e sedimento na Praia do Futuro (Fortaleza-Ceará), coordenado pelo Prof. Dr. Rivelino Martins.

-Aos meus pais e a todos os meus familiares que me apoiam nessa trajetória!

-A todos os amigos que de alguma forma me incentivam a continuar nessa jornada!

-As boas energias!!!

RESUMO

A dessalinização da água do mar é uma alternativa para suprir a demanda por água para o abastecimento humano e industrial em regiões com escassez hídrica. Embora essa atividade forneça uma série de benefícios socioeconômicos, existe uma preocupação crescente com os impactos ambientais. Alguns organismos podem ser mais sensíveis a esses impactos, a exemplo do plâncton, um importante componente da biota marinha que responde rapidamente às alterações ambientais. Diante da perspectiva de crescimento das usinas de dessalinização e dos impactos associados, fazem-se necessárias novas pesquisas científicas que venham entender e mitigar possíveis problemas. O objetivo dessa tese de doutorado foi fornecer uma visão geral sobre os impactos das descargas de dessalinização na comunidade planctônica por meio de diferentes abordagens. No Capítulo 1, realizou-se uma revisão global sobre o assunto. Em seguida, nos capítulos 2 e 3, realizou-se um diagnóstico prévio da estrutura do fitoplâncton (Capítulo 2) e mesozooplâncton (Capítulo 3) na região onde será implantada a maior usina de dessalinização no Atlântico Sudoeste (Fortaleza, Brasil). Diante da revisão realizada e publicada na revista *Science of the Total Environment* (Capítulo 1), foi possível concluir, com base em estudos ao redor do planeta, que o fitoplâncton se mostrou mais sensível às descargas das usinas, quando comparado ao zooplâncton. As principais alterações foram diminuição da produtividade primária, perda de diversidade e alteração na estrutura da comunidade por domínio de grupos tolerantes a altas salinidades. Esses impactos podem variar de acordo com as características das espécies no local de impacto, circulação de correntes oceânicas e marés do local de descarga, bem como a composição e concentração dos efluentes. Vale ressaltar que ainda existe um número muito limitado de estudos que avaliaram a influência das descargas na comunidade planctônica. Com relação ao levantamento prévio da comunidade fitoplanctônica antes da instalação da usina de Fortaleza (Capítulo 2), observou-se que as diatomáceas e os dinoflagelados foram os grupos mais representativos. Quatro espécies consideradas nocivas apresentaram maiores densidades durante o estudo, com destaque para *Trichodesmium erythraeum,* uma cianobactéria produtora de toxinas potentes (saxitoxina e palitoxina) e formadora de grandes florações, podendo gerar prejuízos ao bom funcionamento das usinas de dessalinização de água do mar. Suas maiores densidades médias foram observadas para o período seco (745 ± 886 org./L) e as menores no período chuvoso (281 ± 779 org./L). No Capítulo 3, apresenta-se que o mesozooplâncton foi composto prioritariamente por copépodes, com 19 espécies em três ordens (9 calanoidas; 8 cyclopoidas e 2 harpactcoidas), com destaque para *Temora turbinata* (espécie exótica) e *Paracalanus spp.*, que dominaram a comunidade com as maiores densidades, compreendendo cerca de 84% da abundância total. A análise de correspondência canônica (CCA) mostrou que esses organismos tiveram correlacionados aos parâmetros como pH, oxigênio dissolvido, temperatura e clorofila-a, com destaque para a forte correlação positiva de *T. turbinata* com valores mais elevados de clorofila *a*. Os resultados aqui encontrados reforçam a importância de estudos de *baseline* e do monitoramento integrado dessas comunidades afim de detectar potenciais grupos nocivos, bem como, identificar futuros impactos de usinas de dessalinização que venham alterar a estrutura e funcionamento dos ecossistemas marinhos.

Palavras-chave: Dessalinização; Fitoplâncton; Mesozooplâncton; Descarga; Impacto.

ABSTRACT

Seawater desalination is an alternative to meet the demand for water for human and industrial supply in regions with water scarcity. Although this activity provides a number of socio-economic benefits, there is growing concern about environmental impacts. Some organisms may be more sensitive to these impacts, such as plankton, an important member of the marine biota that responds quickly to environmental changes. Given the prospect of growth in desalination plants and the associated impacts, new scientific research is needed to understand and mitigate possible problems. The aim of this doctoral thesis was to provide an overview of the impacts of desalination discharges on the planktonic community using different approaches. Chapter 1 provides a global review of the subject. Then, in Chapters 2 and 3, a preliminary diagnosis was made of the structure of the phytoplankton (Chapter 2) and mesozooplankton (Chapter 3) in the region where the largest desalination plant in the Southwest Atlantic will be located (Fortaleza, Brazil). Based on the review carried out and published in the journal *Science of the Total Environment* (Chapter 1), it was possible to conclude, based on studies around the world, that phytoplankton proved to be more sensitive to discharges from the plants when compared to zooplankton. The main changes were a decrease in primary productivity, a loss of diversity and a change in community structure due to the dominance of groups tolerant of high salinities. These impacts can vary according to the characteristics of the species at the impact site, the circulation of ocean currents and tides at the discharge site, as well as the composition and concentration of the effluents. It is worth noting that there are still a very limited number of studies that have assessed the influence of discharges on the planktonic community. With regard to the previous survey of the phytoplankton community before the installation of the Fortaleza power station (Chapter 2), it was observed that the diatoms and dinoflagellates were groups the most representative. Four species considered to be harmful showed the highest densities during the study, especially *Trichodesmium erythraeum*, a cyanobacterium that produces potent toxins (saxitoxin and palytoxin) and forms large blooms, which can damage the proper functioning of seawater desalination plants. The highest average densities were observed during the dry season (745 ± 886 org./L) and the lowest during the rainy season (281 ± 779 org./L). Chapter 3 shows that the mesozooplankton was composed primarily of copepods, with 19 species in three orders (9 calanoids; 8 cyclopoids and 2 harpactcoids), with *Temora turbinata* (an exotic species) and *Paracalanus* spp. standing out, which dominated the community with the highest densities, comprising around 84% of the total abundance. Canonical correspondence analysis (CCA) showed that these organisms were correlated with parameters such as pH, dissolved oxygen, temperature and chlorophyll-a, with *T. turbinata* showing a strong positive correlation with higher chlorophyll-a values. The results found here reinforce the importance of *baseline* studies and integrated monitoring of these communities in order to detect potential harmful groups, as well as to identify future impacts of desalination plants that may alter the structure and functioning of marine ecosystems.

Keywords: Desalination; Phytoplankton; Mesozooplankton; Discharge; Impact.

LIST OF FIGURES

CHAPTER 1 - **Impacts of desalination discharges on phytoplankton and zooplankton: perspectives on current knowledge**

CHAPTER 2 - **Implementation of the largest desalination plant in the south atlantic: first diagnosis of the marine phytoplankton before the plant.**

CHAPTER 3 **- Diagnosis of the zooplankton community under the influence of a future large-scale desalination plant (Brazilian Semiarid Coast).**

LIST OF TABLES

CHAPTER 1 - **Impacts of desalination discharges on phytoplankton and zooplankton: perspectives on current knowledge.**

CHAPTER 2 - **Implementation of the largest desalination plant in the South Atlantic: diagnosis of the marine phytoplankton before the plant.**

CHAPTER 3 **- Diagnosis of the zooplankton community under the influence of a future large-scale desalination plant (Brazilian Semiarid Coast).**

SUMMARY

1. General introduction

Water is a highly useful resource, used for human and industrial supply, food production, energy generation, as well as being a biochemical component of living beings and a fluid habitat for many species (TUNDISI, 2008). Ocean waters comprise approximately 97.5% of the total volume of water on Earth, but only 2.5% of this amount is fresh water, with a large part of this fresh water (68.9%) forming the polar ice caps, snow and glaciers and only 0.3% being available in rivers and lakes (REBOUÇAS, 2006). However, the availability of fresh water for human consumption is becoming scarcer every day due to irresponsible consumption, low reuse, climate change and the loss of water quality (UNESCO, 2020).

In arid and semi-arid regions, the situation of water scarcity is aggravated by the growing expectations of the effects of global climate change and pollution, coupled with the reduced availability of surface and groundwater, both quantitatively and qualitatively (ZHANG et al., 2017; KAHIL et al., 2015; IPCC, 2007). Around 60% of the world's population live in regions affected by increasing water stress. It is projected that by 2030 global water demand will exceed supply by 40% and that around 6 billion people will be in a situation of water scarcity by 2050 (UNPD, 2020). Improving the availability of fresh water therefore represents an enormous technological and environmental challenge for humanity, especially in these regions with extreme climates.

Research and technological innovations are essential to tackle the problem of the availability and quality of water resources, given the vulnerability of water systems in various countries (DESCHEEMAEKER et al., 2010; BATISANI & YARNAL, 2010). Seawater desalination technology has become an important alternative for supplying water to the population (ELIMELECH and PHILLIP, 2011; MAUTER and FISKE, 2020; SHAH et al., 2022). Countries in the Middle East were the first to adopt desalination technology to supply water on a large scale, due to the great limitation of drinking water because of the region's aridity (ROBERTS et al., 2010).

Desalination plants use two main technologies: thermal or membrane (NASSRULLAH et al., 2020). Initially, the thermal process was quite widespread, but nowadays reverse osmosis membrane technology is gaining prominence (GREENLEE, 2009; LIM et al., 2021). Desalination by reverse osmosis consists, in general, of removing salts by filtering saline water through selective membranes under high pressure (SAMIAT, 2000). The most widespread thermal processes are multi-stage flash and multi-effect distillation, both technologies use high temperatures to distil saline water and obtain fresh water (IHSANULLAH, et al., 2021). Other technologies such as direct osmosis, steam compression distillation, electrodialysis, reverse electrodialysis and capacitance deionization are also used, but on a smaller scale (JONES et al., 2019). Over time, technological progress has been made to develop and make the desalination process economically viable (AL-KARAGHOULI et al., 2013).

Desalination plants are operating on all continents and there is a prospect of this activity expanding in the coming years (VIRGILI, 2015), with emphasis on reverse osmosis technology. Currently, the largest number of plants in operation are in the Middle East, followed by North America, Asia, Europe, Africa, Central America, and South America (SHARIFINIA et al., 2019). Brazil is a very incipient country in terms of this technology (SILVA et al., 2018), although it is a country with several problems related to the distribution of drinking water to the population (VAL et al., 2019), especially in the semi-arid areas of the country. But factors such as population growth, droughts and climate change could force the increased use of this technology in the country in various areas (MOREIRA et al., 2021). This is the case with the implementation of the largest desalination plant in Brazil, which will be installed in the state of Ceará, a semi-arid region with a history of water shortages. The plant will use reverse osmosis technology and will be located in Praia do Futuro, in the municipality of Fortaleza (state capital). It will have a production capacity of 1.0 m^3/s of treated water, which will serve approximately 700,000 people when it is operational (PEREIRA et al., 2021).

The reverse osmosis technology is currently the most widely used, accounting for 62% of the world's desalinated water production, while thermal distillation processes account for 29% (SHARIFINIA et al., 2019). These technologies release effluent discharges into the sea after the desalination process, and the physical and chemical composition and concentration of these discharges can vary according to the technology used (ROBERTS et al., 2010). In general, the effluents are composed of high concentrations of salts that can reach up to 80g/L, high temperatures of up to 10ºC above ambient, low or no dissolved oxygen, organophosphonates or polyphosphonates (antifouling agents) that can increase the amounts of phosphorus in the water and varying concentrations of heavy metals (LE QUESNE, et al., 2021).

These factors together (high temperature, high salinity, and chemical compounds) can alter the marine biota of regions close to the plants' discharges and some species can respond negatively to the effluents generated in the desalination process (SHARIFINIA et al., 2019). Plankton are one of these biotic components that can change because of the environmental impacts generated by desalination plant discharges in the area of direct influence of the plants (ROBERTS et al., 2010). They can therefore be important indicators of the state of the marine environment affected by desalination projects.

Plankton is a group of organisms that make up aquatic ecosystems and includes, for example, phytoplankton and zooplankton (ESTEVES, 2011). When we consider the entire food web, these components are interconnected. Phytoplankton and zooplankton form the base of the food chain and are extremely important for subsequent trophic levels (FRANCESCHINI, 2010; LEE, 2008), as well as being fundamental for the carbon cycle and nutrient cycling in the oceans (PADFIELD et al., 2018, FALKOWSKY et al., 2004). Changes in the structure of planktonic communities can cause serious damage to aquatic organisms and coastal environments (BOERSMA et al., 2008; PIERSON, 2018).

The construction of the plants, the emission of atmospheric pollutants and the entrainment of marine biota are some of the impacts attributed to desalination plants (LEE & JEPSON, 2021). But the main ones are related to the discharge of effluents with high salinity and high temperature, as well as a variety of chemicals that can cause adverse effects on water quality, harming marine life and the integrity of coastal ecosystems (LE QUENSNE et al., 2021; BELKIN et al., 2017). Understanding the possible impacts of the exponential use of desalination plants on plankton biodiversity is an important topic for the sustainable development of coastal zones.

Larger marine organisms (e.g. fish) can be sucked in by the intake structure and become trapped in an initial screening screen, while smaller ones (e.g. phytoplankton and zooplankton) are dragged and enter the water flow into the plant. The impact of this trapping and dragging can vary depending on the configuration of the plant (MISSIMER and MALIVA, 2018). The accumulation of marine organisms in the plant's catchment area can also jeopardize the water supply for the desalination process by partially or completely blocking the water intake (IHSANULLAH et al., 2021). In 2008, several reverse osmosis plants had to stop operating due to the high biomass reached by the dinoflagellate *Cochlodinium polykrikoides* in the Persian Gulf and the Sea of Oman (SAEEDI et al., 2011), which could cause clogging in the filtration system and also produce unpleasant compounds that would affect the quality of the treated water.

In addition to the impacts related to the dragging of biota, there is also concern about thermal effluents (LE QUENSNE et al., 2021). Water temperature has a major influence on plankton, as it acts directly on reproduction and controls metabolic rates through effects on the enzymatic activities of organisms (SOMERO, 1995). Some authors report that temperature is one of the main factors altering the zooplankton community, contributing to changes in diversity, abundance, and species composition (VILAS-BOAS et al., 2021; WANG et al., 2021; ZAO et al., 2022). According to Hilligsøe et al. (2011), temperature can influence the size of phytoplankton cells, i.e. as the temperature rises, there is a decrease in larger cells in the community structure, affecting specific primary consumers. The intensification of temperatures in effluents can cause damage to marine organisms, reducing species and increasing mortality near disposal areas (LATTEMANN and HÖPNER, 2008; CHANG, 2015).

The brine released into the marine environment after the desalination process can also affect aquatic organisms. In this context, reverse osmosis plants can release brine with a higher amount of salts compared to thermal distillation (KHAN and AL-GHOUTI, 2021). Brine can induce necrosis in the tissues of marine organisms and make them more susceptible to environmental changes, as well as inducing physiological changes and altering the composition of the biological community (GACIA et al., 2007; DEL PILAR RUSO et al, 2007). The excessive amount of salt generates osmotic stress in organisms, causing cell dehydration due to a decrease in turgor pressure, and this biological impact can lead to the death of some benthic and planktonic species (BELKIN et al., 2015; Garrote-Moreno et al., 2014). Some osmoadaptive species can excel when subjected to varying levels of salinity (KIRST, 1990). In this context, Bharathi et al. (2022) reported that there was a lower diversity of phytoplankton when the salinity level of the environment studied was raised, selecting some groups such as diatoms.

The chemical composition of effluents is another problem related to desalination activities. For example, chlorine is used in incoming water to prevent the formation of biofilms (FUJIWARA and MATSUYAMA, 2008). However, a portion of this chlorine reaches the marine environment through effluents (DAWOUD, 2012) and even if it is diluted at the point of discharge, the risk still exists, as chlorine and its derivatives have a toxicological effect on marine biota (HAMED et al., 2017).

Coagulants are also widely used to help aggregate suspended particles and thus facilitate their retention in the filtration system (LATTEMANN and HÖPNER, 2008). Some products such as iron hydroxide, aluminum hydroxide and ferric chloride are used as coagulants (BELKIN et al., 2017; SADHWANI at al., 2005). These compounds are characterized as having low toxicity for aquatic environments (LEWANDOWSKA and KOSAKOWSKA, 2004; LATTEMANN and HÖPNER, 2008), however, they can cause damage to the planktonic community when they are released into the environment, as they alter photosynthesis due to the increase in turbidity at the site of influence of the backwash discharges, as well as inducing the aggregation of these organisms, impacting the structure of the community (BELKIN et al., 2017; CHANG, 2015).

In addition to coagulants, antifouling agents are also used in the desalination process to prevent fouling of the internal structures of the plants (LE QUENSNE et al., 2021). Phosphonates (organophosphonates and polyphosphonates) are the most commonly used. These compounds contain phosphorus in their composition and can increase the concentration of this nutrient at the discharge sites. Another compound used, but in smaller quantities, is polyphosphate, a substance that also contains phosphorus in its composition (LATTEMANN and HÖPNER, 2008). This nutrient is of fundamental importance for primary productivity and an increase in its concentration can cause disturbances in the ecology of the aquatic environment (SCHELSKE, 2009).

Another problem related to desalination discharges is the release of toxic metals into the marine environment. These metals can come from the corrosion of metal structures, as well as from some corrosion inhibitors used in the desalination process (VAN DER BRUGGEN et al., 2003; LA QUENSNE et al., 2021; CHANG, 2015). Toxic metals represent a series of impacts on organisms and ecosystems, due to their toxicity and persistence in the environment, so they are considered important contaminants in marine environments (RUILIAN et al., 2008; DE FOREST et al., 2007). These metals can biomagnification in marine organisms along the food chain (MACHADO et al., 2015) and also alter the abundance, richness and diversity of some aquatic species (VAN REGENMORTEL et al., 2018). In addition, they can impact the planktonic community, causing changes in its structure (SATHICQ and GÓMEZ, 2018; GRIBOFF et al., 2018).

Given the expansion of desalination activities and the concern about possible impacts on planktonic organisms, this Ph.D thesis aimed to generate novel information that will improve understanding of the impacts of desalination discharges on the planktonic community, with information organized into 3 chapters to be published in international journals.

Chapter 1 is a review of research already published, with the aim of assessing the influence of discharges from different desalination technologies on plankton, both in field studies and in research carried out in laboratories, and this chapter has already been published in the high-impact journal *Science of The Total Environment*. Chapter 2 deals with a diagnosis of the phytoplankton community where a seawater desalination plant will be installed and is due to be submitted to the journal *Desalination* (Elsevier). And to finish the thesis, chapter 3 is a baseline assessment of the zooplankton community with an emphasis on copepod assemblages and is due to be submitted to the journal *Marine Pollution Bulletin* (*Baseline journal section*). Both chapters (2 and 3) should be submitted to international journals after review by the doctoral thesis examining board.

2. Objectives

2.1. General objectives

To contribute with novel information on the impacts of desalination plant discharges on plankton through a review of worldwide published science, as well as to generate a baseline study related to the structure of plankton communities before the implementation of a seawater desalination plant (Fortaleza, Brazil) and thus provide a history for future comparisons in the structure of these organisms.

2.1. Specific objectives

a) To review the reported global impacts of desalination plants on the phytoplankton and zooplankton community by reviewing published studies;

b) To carry out a baseline diagnosis of the structure of the phytoplankton and zooplankton community, with an emphasis on copepod assemblages, in a region of Praia do Futuro - Brazil, where the largest reverse osmosis desalination plant in the Southwest Atlantic will be installed.

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CHAPTER 1 - Impacts of desalination discharges on phytoplankton and zooplankton: perspectives on current knowledge

Science of the Total Environment 863 (2023) 160671

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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Discussion

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

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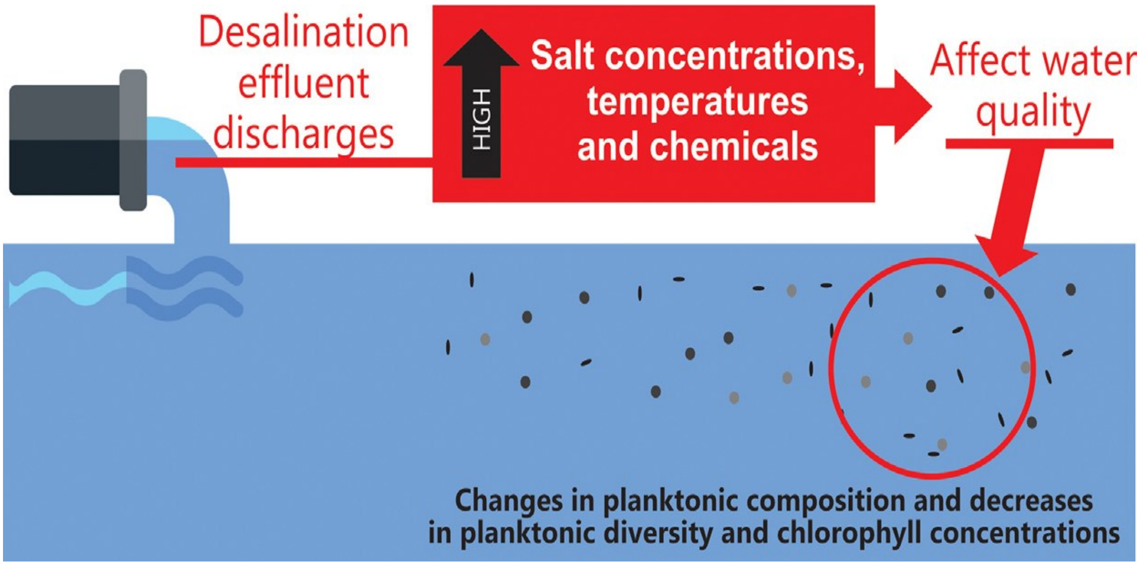
Abstract

Seawater desalination represents an alternative means to meet the human, industrial, and agricultural water demand in water-stressed regions and is expected to increase in number and geographic coverage as global climate change intensifies. However 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 impacts of desalination plant discharges: 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, considering both laboratory and field studies, 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 escalete 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.

Keywords: Phytoplankton; Zooplankton, Desalination, Brine, Discharge; Effluent

Graphical Abstract



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 & PHILLIP, 2011). 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. 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.

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 (SAMIAT, 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 01).

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, 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).

Table 1- Advantagens and disadvantagens 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

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; LATTEMANN 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., 2014). 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., 2020). 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 (Figure 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 et al 2015; FERNÁNDEZ-TORQUEMADA et al 2009; LOYA et al 2012, 2018; SOLA et al 2020).

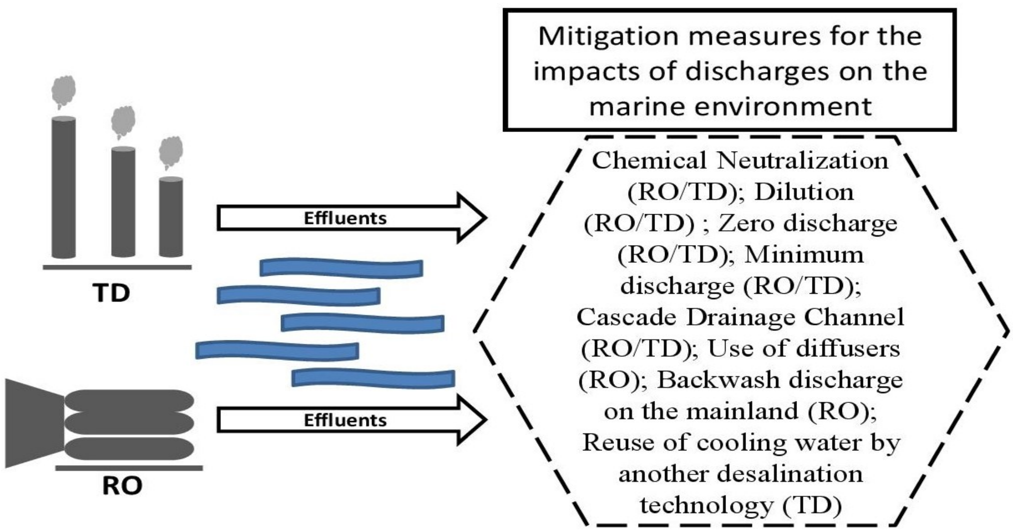


Figure 1-Measures to mitigate the impacts of effluents practiced in the TD and OR plants.

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-TORQUEMEDA 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., 2021), further research is needed to mitigate their impacts on marine plankton biodiversity. However, this topic has not been reviewed 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.

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%) (Figure 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 (Table 2). 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 QUENSNE et al., 2021; BELKIN et al., 2017).

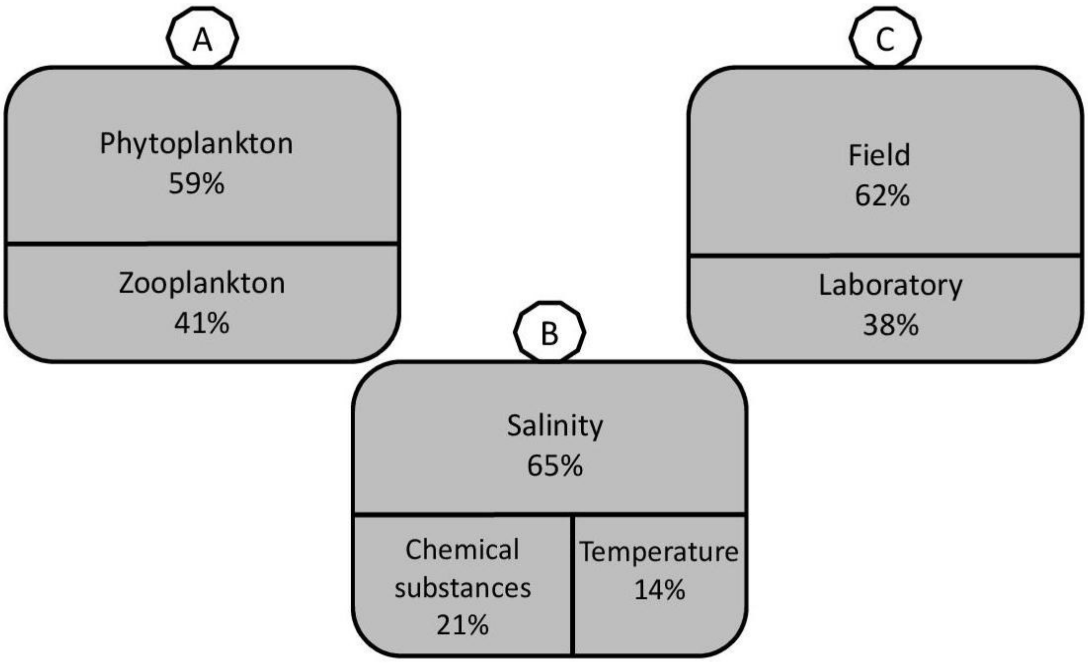


Figure 3- Analysis of desalination published studies focusing on zooplankton and phytoplankton (A), salinity, temperature and chemical impacts (B), and laboratory and field studies (C).

Table 2- General characteristics of effluents from MSF, MED and RO plants.

Parameters	MSF/MED	SWRO
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 beteween 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, aluminium 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)

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 (AZIZ et al., 2003; OZAIR et al., 2017; SAEED et al., 2019), which will be discussed along this section (Table 3).

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 (1mg 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)

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 QUENSNE 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 (LATTEMANN 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).

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

References	Location/Region	Temperature difference (ºC)	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

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., 2018). 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

HOPNER, 2008). The effects of brine from desalination plants on marine planktonic organisms varied; some groups were more sensitive than others (Table 5).

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 coastatum, Chlorella vulgaris, Tetraselmis suecica, Isochrysis galbana.*
		>65 ppt	50% mortality.	*Brachinonus 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, Brachinonus 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.	

4.3.1. Laboratory investigations

Laboratory studies tested salinity values usually observed in discharges from desalination plants (38–90 ppt). Yoon and Park (2011) obsrved 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 *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. 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 (LATTEMANN 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; Sadhwaniat al., 2005; LATTEMANN 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., 2014). 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 (LATTEMANN 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 although there is degradation and dilution of total chlorine in the marine environment after discharge, environmental risks still exist (LATTEMANN 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 mgCl/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 (LATTEMANN 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; SADHWANIAT et al., 2005). These substances have low toxicity in aquatic environments (LEWANDOWSKA and KOSAKOWSKA, 2004; LATTEMANN 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 QUENSNE 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., 2018). 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 (LATTEMANN 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 QUENSNE 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 (SATHICQAND-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 relevant 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.

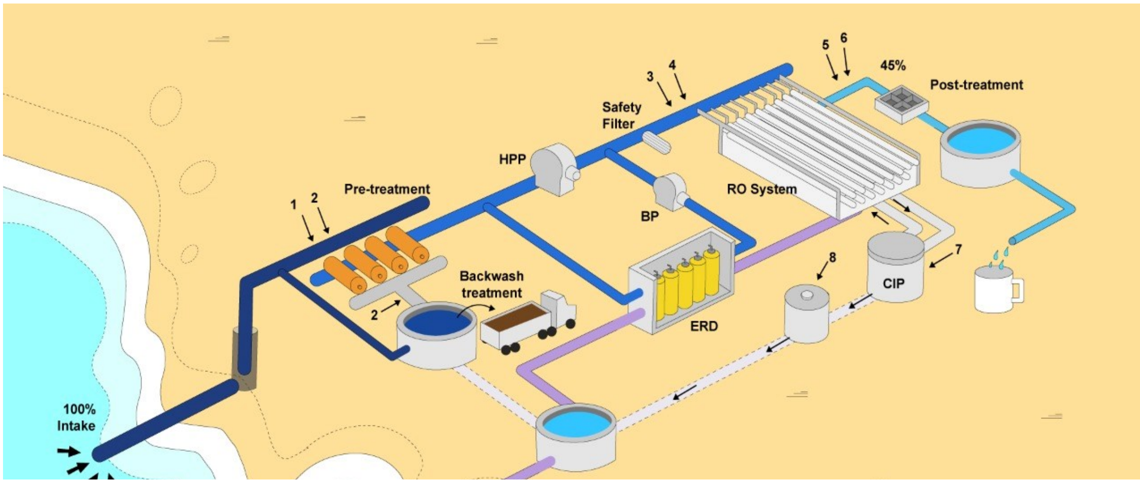


Figure 5- Typical arrangement of a SWRO desalination process. Biocides (1) and coagulants (2) products are applied on the raw water, whereas dichlorination (3) and antifouling (4) agents are added before the RO membranes. Acid and alkaline products and dichlorination agents (8) are used to neutralize 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 CO2 and CaCO3. RO: reverse osmosis. HPP: high-pressure pump. BP: booster pump. ERD: energy recovery device. Source: author.

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.

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CHAPTER 2 – Implementation of the largest desalination plant in the South Atlantic: diagnosis of the marine phytoplankton before the plant.

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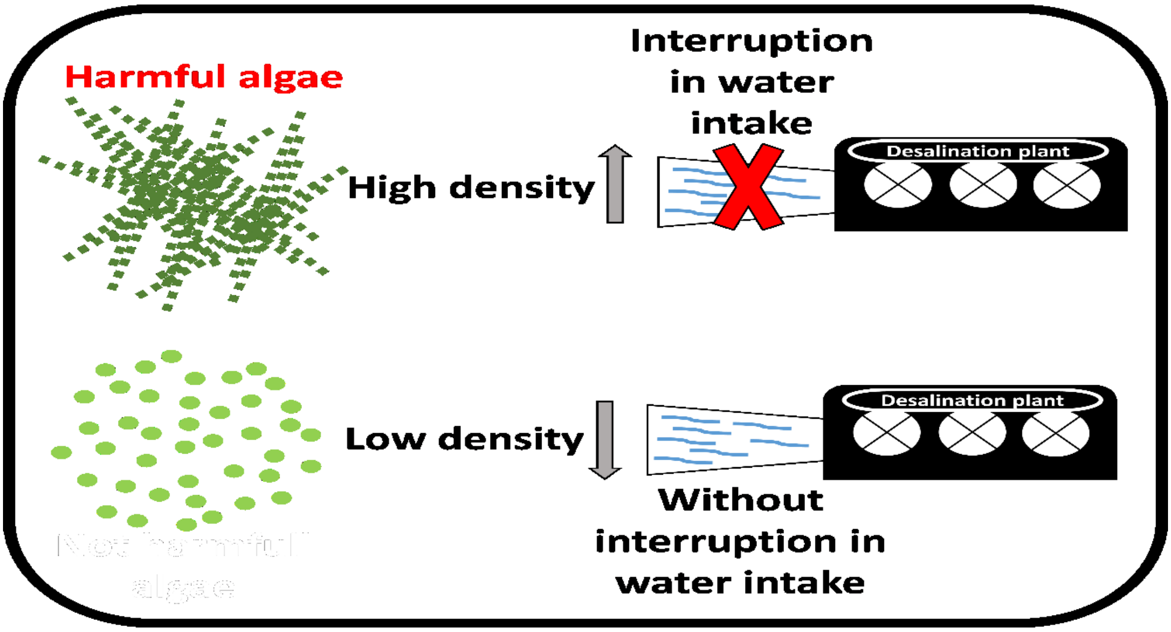
Abstract

Water scarcity is a problem affecting many regions worldwide, especially arid and semi-arid areas. In this context of present and future scarcity, seawater desalination technology emerges as an alternative for supplying water to the population. However, there is some concern related to the impacts generated by the activity effluents on marine organisms, including phytoplankton. The aim of this baseline study was to carry out a spatio-temporal assessment of the structure and dynamics of phytoplankton in a region where the largest seawater desalination plant in the Southwest Atlantic (Brazil) will be installed. Water sampling was carried out in 2020 and 2021, during the dry and rainy seasons at the plant's planned intake and outfall points, as well as at two depths (subsurface and bottom), and occurred along with the measurement of environmental variables such as pH, temperature, total suspended solids, chlorophyll-a, conductivity, and salinity. With regard to the physical and chemical parameters, the greatest variations were observed for the year 2020 (ΔpH= 0.74; ΔSalinity= 1.2; ΔChlorophyll-a= 0.412 $\mu g.L^{-1}$; ΔTotal suspended solids= 4.8 $mg.L^{-1}$), except for conductivity (Δ= 1,936 $\mu S.cm^{-1}$) and temperature (Δ= 1.5 TºC), where the greatest variations were observed in 2021. The principal component analysis (PCA) revealed that temperature was the parameter that best explained the variations in the environmental data and that the rainy seasons had a positive relationship with this parameter, as well as conductivity and total suspended solids. The results of the canonical correspondence analysis (CCA) also showed that temperature was the most influential parameter on the variation of the data set and that some harmful microalgae species (*Prorocentrum micans*, *Chaetoceros* spp. and *Gyrodinium* spp.) had a positive correlation with this variable. Spatial and seasonal variations were observed in the phytoplankton community and the most representative groups were diatoms and dinoflagellates. The highest average density was observed in 2021, at the dry period catchment point, with a value of 26,360 ± 10,287 org./L and the lowest was in 2020, at the wet period outfall point, with an average value of 7,698 ± 3,338 org./L; that is, about three times lower than the dry period. The highest values for the density, richness and diversity were observed in the dry period. Among the most representative species, four are classified as harmful: *Trichodesmium erythraeum* (cyanobacterium), *Chaetoceros* spp. (diatoms), *Prorocentrum micans* and *Gyrodinium* spp. (dinoflagellates). In this study, *T. erythraeum* was the species with the greatest potential for damaging the desalination plant, as it forms large blooms and can cause the filters at the water collection point to clog, as well as producing potent toxins that cause problems for human health.

Keywords: Phytoplankton; Harmful algae; Environmental variables; Marine environment; Human impacts; Effluent damage.

Graphical abstract



1. Introduction

The desalination of seawater meets the demand for drinking water for the population, especially in arid and semi-arid regions, and the use of this technology is growing every year (AYAZ et al., 2022; VIRGILI, 2015). Although it is an alternative to mitigate water scarcity, there are also concerns about the negative ecological impacts caused by the plants (ELIMELECH & PHILLIP, 2011). In the case of the marine environment, the impact is related to the dragging and trapping of marine organisms at the water intake point and also to the discharge of effluents after the water desalination process (MISSIMER & MALIVA, 2018; LATTEMANN & HÖPNER, 2008). These effluents can contain high salinity, high temperature and residues of chemical substances used during the desalination process (LATTEMANN & HÖPNER, 2008; LE QUESNE, et al., 2021). Desalination discharges can cause changes to marine organisms, especially sensitive ones, such as members of the phytoplankton community (GOMES et al., 2023; ROBERTS et al., 2010).

Monitoring biological communities, including phytoplankton, is extremely important for understanding the dynamics of these groups in regions impacted by human activities (ZHANG et al., 2023; PICONE, et al., 2023; GENITSARIS, et al., 2023; XIONG, et al., 2020). The lack of prior diagnostics (baseline) hinders the assessment of environmental impacts, such as what happened in the city of Mariana (Minas Gerais, southeastern Brazil), in which the scarcity of previous studies of biological communities made it difficult to assess the impact on the dynamics and structure of aquatic populations affected by the spillage of tailings from the collapse of the dam of a large mining company (CARMO et al., 2017; FERNANDES et al., 2016).

Phytoplankton have already been shown to be sensitive to desalination discharges (GOMES et al., 2023), which is worrying as they are one of the main components of aquatic environments (PAERL & JUSTIĆ, 2011). Phytoplankton are fundamental to ecosystems, as they act as primary producers, accounting for around 45% of all annual primary productivity (FALKOWSKY et al., 2004), it is a key player in nutrient cycling (LIE et al., 2011, WEBER and DEUTSCH, 2012), in addition to being responsible for fixing a large part of global carbon, absorbing millions of tons of inorganic carbon per day (PADFIELD et al., 2018; BEHRENFELD et al., 2006), thus helping to control the planet's climate by depleting carbon dioxide (CARVALHO et al., 2021). Another important aspect is that these organisms have a very short life cycle and respond quickly to physical and chemical changes, such as variations in nutrients, temperature, and salinity (MARGALEF, 1983), which makes them excellent environmental indicators (BARTON et al., 2015) including for assessing the impacts of desalination plants.

The diatoms, dinoflagellates and haptophytes are some of the groups that stand out in the marine environment and among these groups, with some species being considered harmful. Harmful algae are considered important ecosystem stressors worldwide, because they can produce toxins and are also capable of forming large harmful algal blooms (HABs) (BERDALET et al., 2017), posing a risk to water abstraction in desalination plants.

The effects of HABs include public health risk, fish and wildlife mortality, ecosystem disturbance, hypoxia or anoxia in high biomass blooms and harmful impacts associated with the accumulation and decomposition of large microalgae blooms (ANDERSON et al., 2021; LÓPEZ-CORTÉS et al., 2019; BATES et al., 2018; IMAI et al., 2006; HALLEGRAEFF et al., 2003; SALA et al, 1998; BRUNO et al, 1993). In addition to affecting fisheries and aquaculture, HABs raise the possibility of loss of water quality or interruption of supply in desalination plants (UNESCO, 2017; RICHLEN et al., 2010; BOALCH & HARBOUR, 1977).

In view of the environmental impacts related to desalination discharges, this baseline study aimed to assess the phytoplankton community structure (density, richness, diversity and composition), considering spatial and seasonal factors, as well as the influence of environmental variables (temperature, salinity, pH, conductivity, chlorophyll-a and total suspended solids) in Praia do Futuro (Ceará, Brazil), where a reverse osmosis desalination plant will be installed. The plant will be the largest in Brazil, with a production capacity of 1.0 m^3 /s of treated water that will serve 700,000 people (Governo do Estado do Ceará, 2021). The brine will be discharged via an underwater outfall located 1.2 km from the coastline and will have a flow rate of 1.23 m^3/s (PEREIRA et al., 2021). Taking into account the size of this large project, the importance of phytoplankton to the aquatic environment and the possible impacts of desalination plants on these organisms, it is of fundamental importance to carry out a diagnosis in order to monitor the environment and track the response of this community to future environmental changes.

2. Materials and methods

2.1 Study area

The study area is located on a stretch of Praia do Futuro (Fortaleza, Brazil) at approximately five kilometers from the mouth of the Cocó River (Figure 1a), a 45 km long river, whose larger area is located in an urban area, thus being an important source of particulate matter for the coastal zone (SCHETTINI et al., 2017). The sampling grid for this study consists of a total of ten points parallel to the coastline, with five points closer to the coast (1 km), called the saline effluent outfall (O1-O5) (where the effluent from the future plant will be discharged), and five points more distant from the coast (2,5 km), called the catchment points (C1-C5) of the desalination plant that will be set up (Figure 1b). The distance between the intake and outfall points is approximately 1 km.

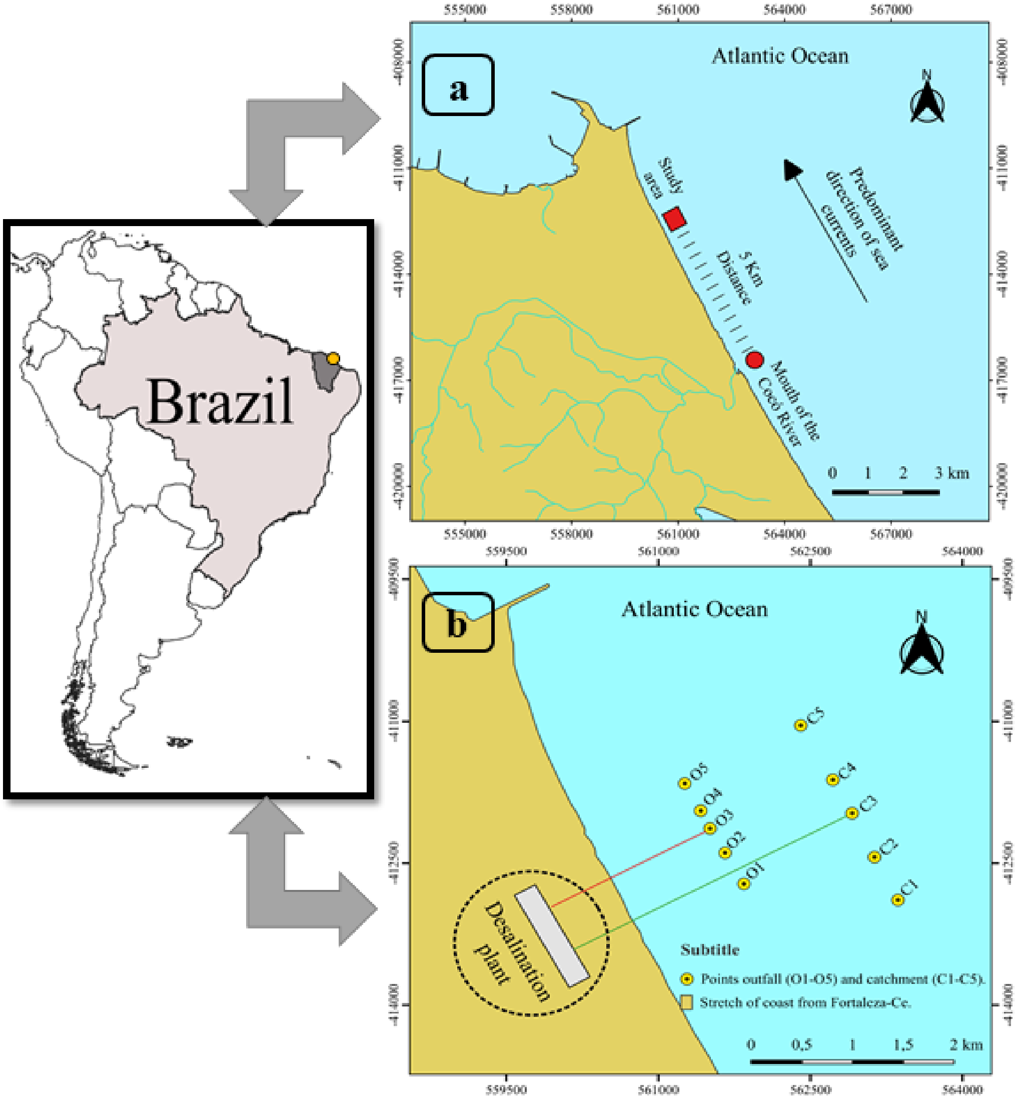


Figure 1- a) Distance between the mouth of the Cocó River and the study area. b) Location of the study area where the desalination plant will be installed on Praia do Futuro (Fortaleza, Brazil) with details of the sampling network. C1-C5 indicate the five catchment points ; and O1-O5, the five outfall points.

The region sampled is part of a stretch of the semi-arid continental shelf in northeastern Brazil (MORAES et al., 2020), with low estuarine inflow and oligotrophic characteristics (MORAES et al., 2020; EKAU & KNOPPERS, 1999), with two well-defined seasonal periods, the dry and the rainy seasons. The rainy periods are between January and May, while the dry periods are between June and December (FUNCEME, 2023) (Figure 2). Average temperatures vary from 24.5 ºC to and 30.0 ºC , while winds intensify on the months of July and November, with average magnitudes varying from 2.0 to 4.0 m.s^{-1} (INMET, 2023) (Figure 2) . The region also has a strong hydrodynamic activity with a predominance of currents induced by westerly winds close to the coast (SOARES & CASTRO FILHO, 1996).

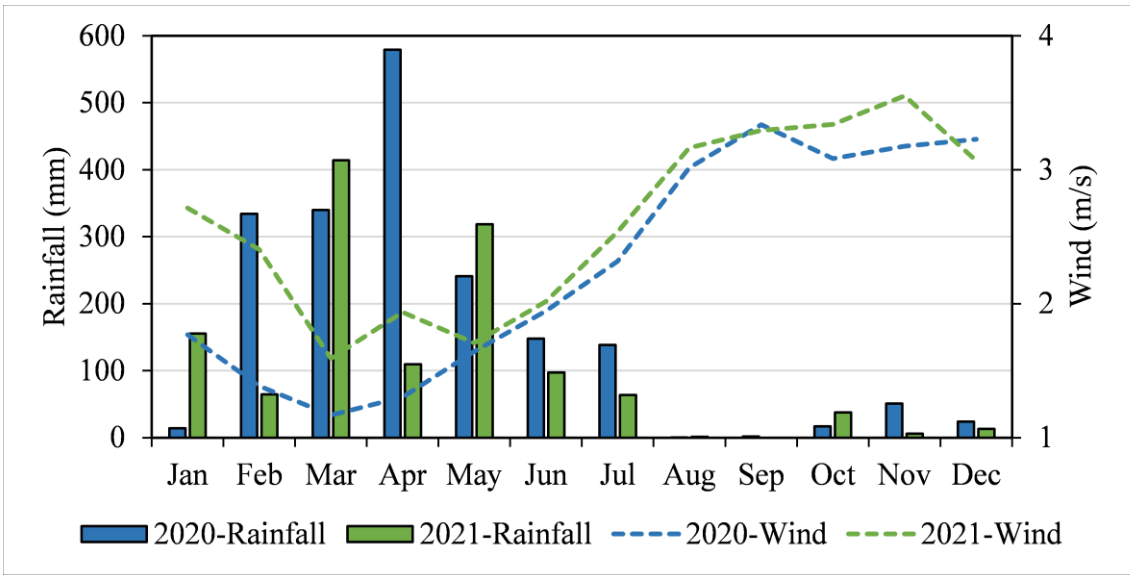


Figure 2- Rainfall and wind graph for the years the research was carried out. Rainy season (1st semester) and dry season (2nd semester). Yellow arrows indicate sampling carried out in 2020 and red arrows indicate sampling in 2021. Data: FUNCEME/INMET.

2.2 Sample collection and analysis

The samples were collected during the dry and rainy periods of 2020 (January and November) and 2021 (February and July), totaling four campaigns (Fig. 2). There were two depth profiles per sampling point: one subsurface and one bottom. The subsurface depth was determined as 30 centimeters from the air-ocean interface for all sampling stations. The bottom depth in the water catchment area varied between 15 and 16 meters, while in the outfall area it was between 12 and 13 meters.

The sampling stations were identified as follows: CSJa = catchment subsurface January ; CBJa = catchment bottom January; OSJa= outfall subsurface January; OBJa= outfall bottom January; CSNo = catchment subsurface November; CBNo = catchment bottom November; OSNo= outfall subsurface November; OBNo= outfall bottom November; CSFe= catchment subsurface February; CBFe= catchment bottom February;

OSFe= outfall subsurface February; OBFe= outfall bottom February; CSJu = catchment subsurface July; CBJu = catchment bottom July; OSJu= outfall subsurface July; OBJu= outfall bottom July.

Sampling for qualitative phytoplankton analysis was carried out using a conical plankton net (20 µm mesh opening, mouth opening diameter 30 cm). Samples for qualitative and quantitative phytoplankton analysis were collected using a Van Dorn bottle (5L volume). A EXO2 multiparameter probe (Yellow Springs Instruments – YSI, Brannum Lane, OH, USA) was used to collect environmental data (pH, total suspended solids, salinity, conductivity, and temperature) *in situ* at both depths. Samples for chlorophyll-a analysis were collected using a Van-Dorn bottle and stored in 5L drums under refrigeration.

The taxa sampled in the net (20 µm) were identified using an optical microscope (Primo Star ZEISS), and some taxa were classified by cell size (µm), when identification at a more specific level was not possible, using magnifications of 100x, 200x, 400x and 1,000x.The samples for quantitative analysis were prepared in Utermohl-type chambers with a volume of 50 mL for 48 hours of sedimentation and analyzed using an Olympus CK2 binocular inverted microscope. The organisms were counted at 400x magnification in alternating vertical transects along half of the chamber, totaling ¼ of its volume and the density (organisms/L) was calculated according to Villafañe and Reid (1995). Chlorophyll-a concentrations were analyzed following the methodology proposed by APHA (1999).

The data used in this work were obtained from the project: Avaliação da variabilidade espaço temporal da qualidade da água e sedimento na praia do Futuro (Fortaleza-Ceará): um estudo anterior à construção da planta de dessalinização do estado do Ceará (LABOMAR, 2022).

2.3 Statistical analysis of data

The data was normalized with a square root transformation and to ensure the same weight for all physical and chemical variables, a "z-value" transformation was used. The Shannon-Wiener diversity index (H'), species richness, density and composition were used to assess the ecological patterns of the phytoplankton community. To check for significant ($p<0.05$) spatial, seasonal and vertical differences in species diversity, richness and density, a parametricity test (Shapiro-Wilker) was carried out followed by one-way (dry and rainy) and two-way (catchment and outfall; subsurface and bottom) analyses of variance (ANOVA), followed by the Tukey test for multiple comparisons.

Species composition was assessed using non-metric ANOSIM test, with a Bray-Curtis index and 9999 permutations. Hierarchical cluster analysis was carried out using the taxa with a relative abundance greater than 5% in at least one of the samples and the sampling stations were grouped according to the Bray-Curtis similarity index. SIMPER analysis was also carried out to test the contribution of the most important taxa to the dissimilarity between groups.

Canonical correspondence analysis (CCA) was performed to explore correlations between phytoplankton and environmental variables (pH, conductivity, salinity, total suspended solids, chlorophyll-a and temperature) and principal component analysis (PCA) was performed to obtain correlations between variables and sampling points. The statistical software package Paleotological Statistics (PAST 4.09) was used to carry out the statistical analyses.

3. Results

3.1 Structure and composition of the phytoplankton community.

Taxa belonging to four groups (cyanobacteria, dinoflagellates, diatoms and euglenophytes) were inventoried, where diatoms stood out with the highest relative abundances throughout the study period, except for the dry period in 2021, where dinoflagellates were more representative. Overall, the highest concentrations of organisms were observed at the catchment stations, with a peak in density in the dry period of 2021, where there was a total average value of 26,360 ± 10,287 org./L (Figure 3).

In 2020, the taxa that contributed the highest relative abundances in the rainy season were *Chaetoceros* spp. (58.26%); and in the dry season, *Cylindrotheca* cf. *closterium* (31.97%). In 2021, *Proboscia alata* (47.12%) had the highest contribution in the rainy season and Peridiniales species (10 - 20 µm) (23.88%) in the dry season. *Chaetoceros* spp. (8,615 ± 16,332 org. /L) and *Proboscia alata* (7,045 ± 2,699 org. /L) were the species that contributed the highest average densities in 2020 and 2021, respectively, both in the rainy season. With regard to depth, there was a higher average density in the subsurface (17,933 ± 9,777 org. /L) when compared to the bottom depth (12,620 ± 5,875 org. /L).

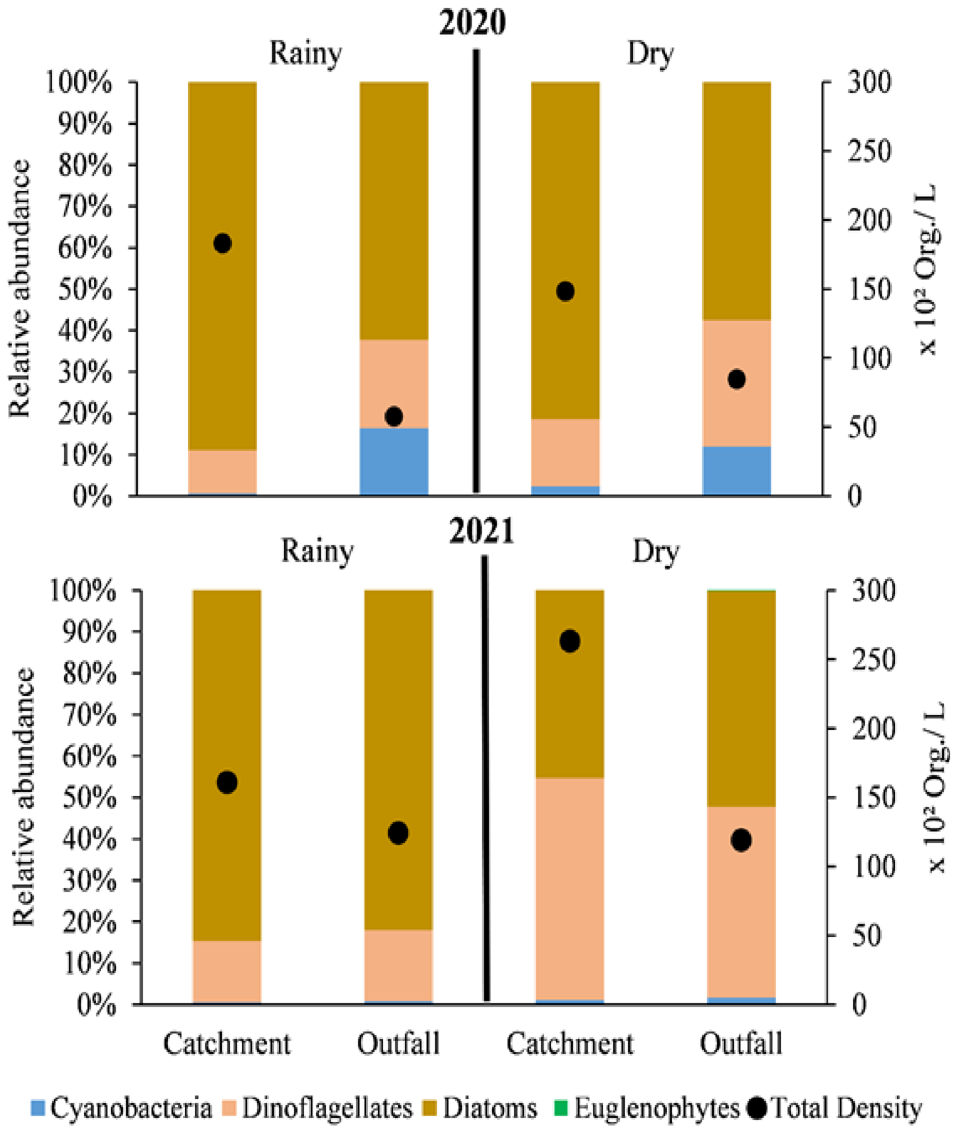


Figure 3- Relative abundance and total density of phytoplankton organisms for the years 2020 and 2021 in the area of the future desalination plant at Praia do Futuro (Fortaleza, Brazil). Data are shown for the rainy and dry periods, as well as the catchment and outfall.

In 2020, there was a higher density of organisms (38,025 ± 20,608 org./L) in the subsurface of the catchment in the rainy season (CSJa), which was significantly different (Tukey test: $p < 0.05$) from the other points sampled in the same year (Figure 3). This high density was due to the increase in *Chaetoceros* spp. (31,275 ± 19,488 org. /L). In the second year, it was noted that the subsurface (30,520 ± 10,317 org./L) and bottom (24,080 ± 8,976 org./L) catchment stations, both in the dry season, stood out with the highest densities. Peridiniales (<10µm) contributed the highest concentrations (8,460 ± 2,686 org./L) in the subsurface of the catchment (CSJu) and Peridiniales (10 - 20 µm) was responsible for the greatest increase in organisms (8,160 ± 5,488 org./L) in the bottom depth of the catchment (CBJu). However, the two stations were not significantly different (Tukey test: $p < 0.05$) (Figure 4). The lowest densities were observed in 2020, with a minimum value of 6,440 ± 3,695 org. /L at the bottom depth of the January catchment (CBJa) (Figure 3).

The highest richness values were found for the year 2021, especially at the dry season stations (CSJu, CBJu, OSJu and OBJu), where values ranged from 26 ± 2 (OBJu) to 32 ± 4 (CBJu) taxa (Figure 4). In 2020, the richness values were lower, ranging from 12 ± 2 (OSJa) to 22 ± 3 (CSNo and CBNo) taxa (Figure 3). Diversity ranged from 2.38 ± 0.1 at the surface of the outfall in the rainy season of 2020 (OSJa) to 3.29 ± 0.1 for the bottom depth of the catchment in the dry season of 2021 (CBJu) (Figure 3). Descriptors such as richness and diversity did not vary significantly between sampling stations in 2020, a fact that did not occur in 2021, where there were significant differences for the same descriptors between sampling stations (Figure 3). This demonstrates the inter-annual variation in phytoplankton in the future desalination plant area.

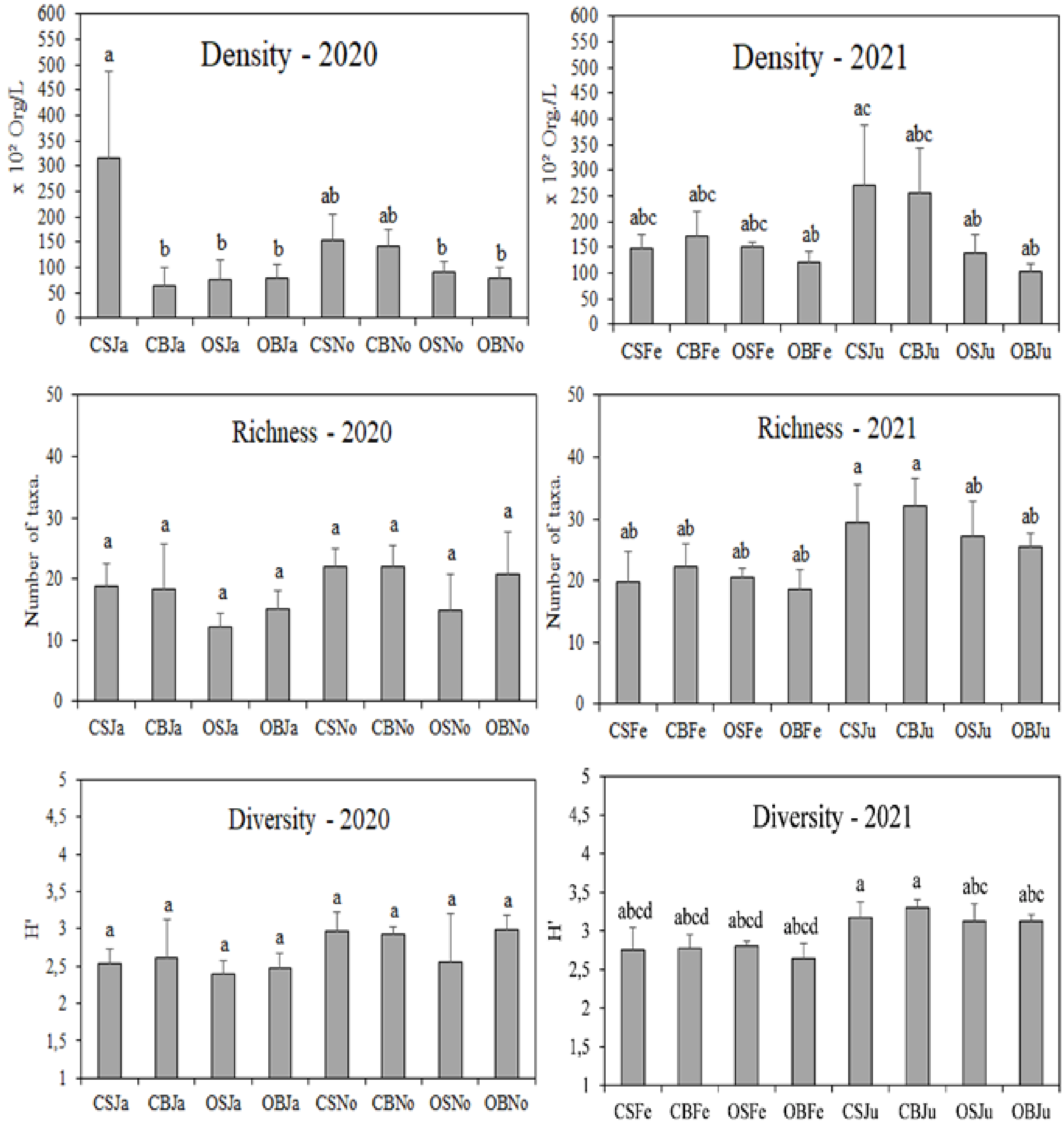


Figure 4- Density, richness (identified to the lowest level when possible) and Shannon-Wiener diversity (H') of the phytoplankton community in the area of influence of the desalination plant, Praia do Futuro (Fortaleza, Brazil). The sampling stations were identified as follows: CSJa = catchment subsurface january ; CBJa = catchment bottom january; OSJa= outfall subsurface january; OBJa= outfall bottom january; CSNo = catchment subsurface november; CBNo = catchment bottom november; OSNo= outfall subsurface november; OBNo= outfall bottom november; CSFe= catchment subsurface february; CBFe= catchment bottom february; OSFe= outfall subsurface february; OBFe= outfall bottom february; CSJu = catchment subsurface July; CBJu = catchment bottom July; OSJu= outfall subsurface july; OBJu= outfall bottom july . Different letters above the bars show statistically different means at the 0.05 significance level (Tukey test).

In general, density was significantly different when the spatial aspect was evaluated, with the exception of 2020, where significant differences were also observed for the vertical factor, due to the high densities of *Chaetoceros* spp. in the subsurface of the catchment point in January (CSJa) (Table 1). Richness and diversity showed significant differences in the seasonal aspect (Table 1).

Diversity was the community descriptor with the least variation during the study, showing significant differences only for the seasonal aspect in 2021 (Table 1). In 2020, the group that contributed the highest densities, both between catchment and outfall and also between seasonal periods, were diatoms, with the *Chaetoceros* spp., *Cylindrotheca* cf. *closterium* and *Thalassionema* sp., species standing out as the most relevant in the total concentration of the group. In 2021, it was noted that diatoms were replaced by dinoflagellates between the rainy and dry periods, where the taxon *Proboscia alata*, a diatom inserted in the microphytoplankton (20-200 µm), was replaced by species of nanoplanktonic dinoflagellates (2.0-20 µm), of the order Peridiniales.

Table 1- Assessment of spatial, vertical, and seasonal variation for indicators (density, richness, and diversity) of phytoplankton in the future desalination plant at Praia do Futuro (Fortaleza, Brazil). ANOVA (Two-Way **; One-Way *; $p<0.05$) for the following factors: Spatial = catchment x outfall; vertical= subsurface x bottom; seasonal= rainy x dry. In red are significantly different values ($p< 0.05$).

		Density		Richness		Diversity	
	Factors	F	*p*	F	*p*	F	*p*
2020	Spatial **	10,44	0,00315	2,4	0,1326	3,692E-06	0,9986
	Vertical **	5,228	0,03	0,3061	0,5845	2,997	0,1585
	Seasonal *	0,00255	0,96	5,272	0,02883	1,311	0,2958
2021	Spatial **	13,52	0,00099	2,711	0,1108	0,2546	0,6404
	Vertical **	1,484	0,2333	0,7036	0,4087	0,0433	0,8453
	Seasonal *	1,788	0,1913	29,25	7,352E-06	21,37	0,0036

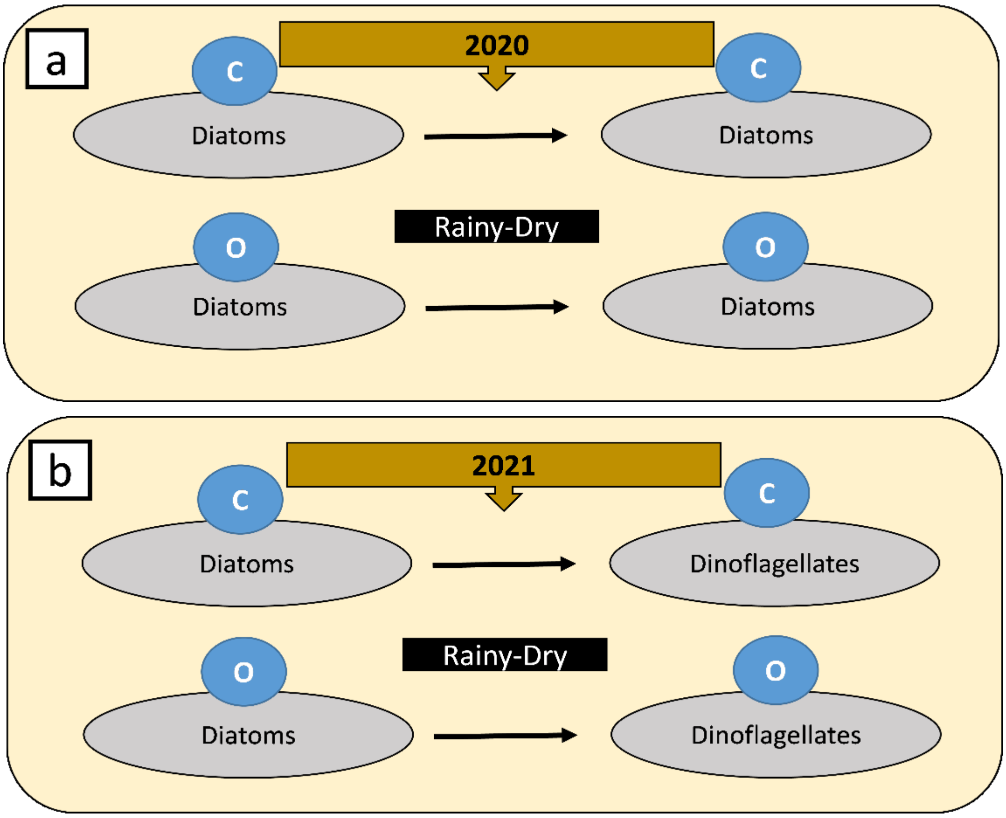


Figure 5- Dominant groups in 2020 (a) and 2021 (b). Catchment (C) and outfall (O). The arrows point to the groups that came to dominate the environment during the transition from the rainy to the dry season, in the region where the desalination plant will be installed (Fortaleza, Brazil).

The similarity analysis showed the formation of five groups, where group 1 was made up of stations from the 2020 dry season, group 2 was made up of stations from the 2021 rainy season, group 3 was made up of stations from the 2021 dry season and groups 4 and 5 were made up of stations from the 2020 rainy season (Figure 6). The SIMPER test showed that *Thalassionema* sp. (9.88%), *Chaetoceros* spp. (9.79%) and *Cylindrotecha* cf. *closterium* (7.98 %) were the taxa that contributed the highest percentages in the dissimilarity of the groups between the dry and rainy periods in 2020. In 2021, *Proboscia alata* (13.22%), Peridiniales spp. (< 10µm) (7.90%) and Peridiniales spp. (10µm - 20µm) (7.52%) were found to be the organisms that contributed most to seasonal dissimilarity.

The groupings showed a seasonal pattern, except for groups 4 and 5, where there was some heterogeneity between the sample stations from the 2020 rainy season (Figure 5). This dissimilarity between groups 4 and 5 was caused by a bloom of *Chaetoceros* spp. (diatom). The SIMPER test showed that *Chaetoceros* spp. contributed with the highest dissimilarity value (27.71 %) between the points from the 2020 rainy season (groups 4 and 5) (Figure 6).

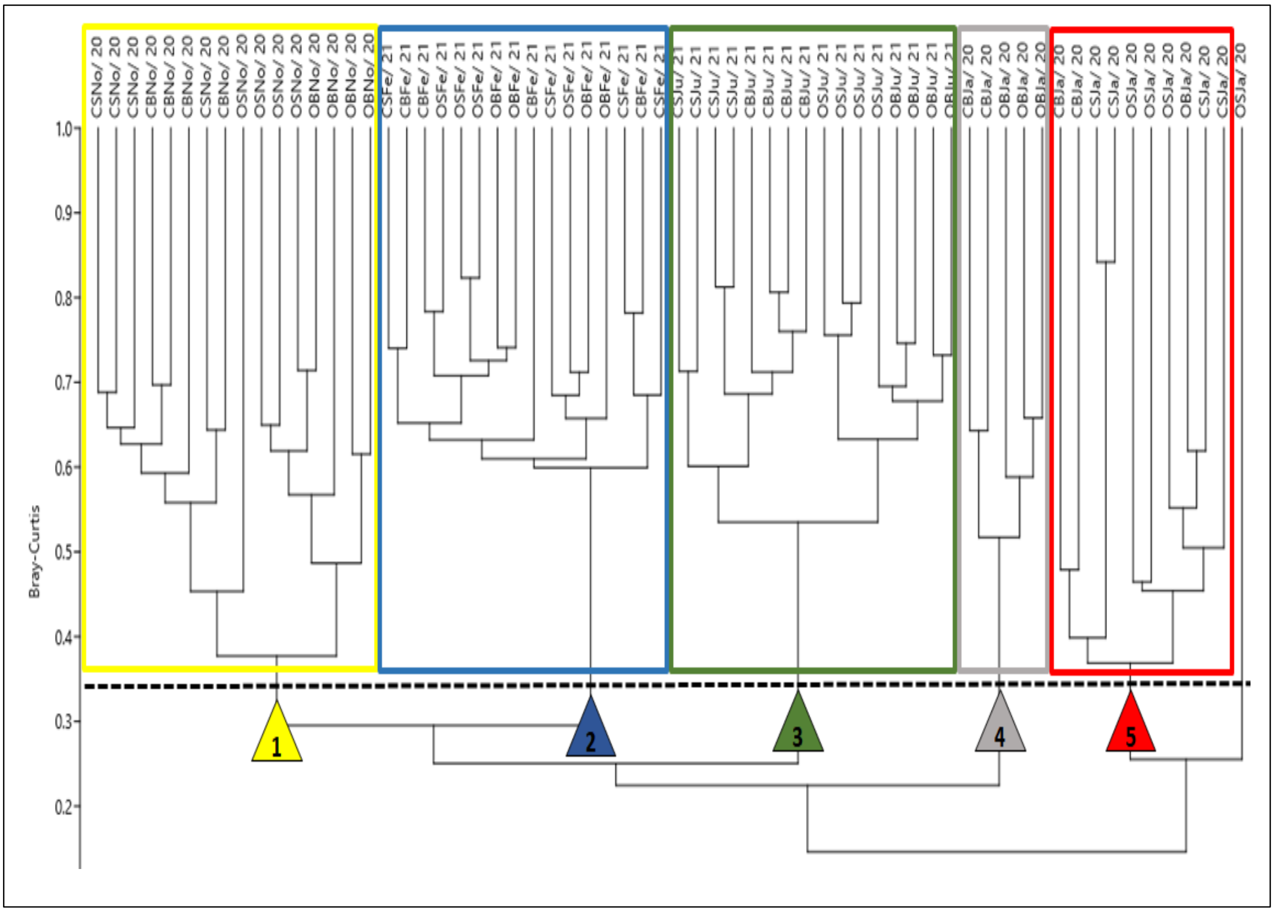


Figure 6- Cluster analysis for the sampling stations based on the phytoplankton community in the area of influence of the future desalination plant, Praia do Futuro (Fortaleza, Brazil). Enumerated triangles show the groups formed based on the Bray-Curtis distance.

The nMDS analysis followed by the ANOSIM test showed a significant ($p<0.05$) seasonal and spatial (catchment x outfall) differentiation in phytoplankton composition. However, the seasonal factor was responsible for the greatest significant difference ($p < 0.05$) between the species composition of the sampling stations (Figure 7).

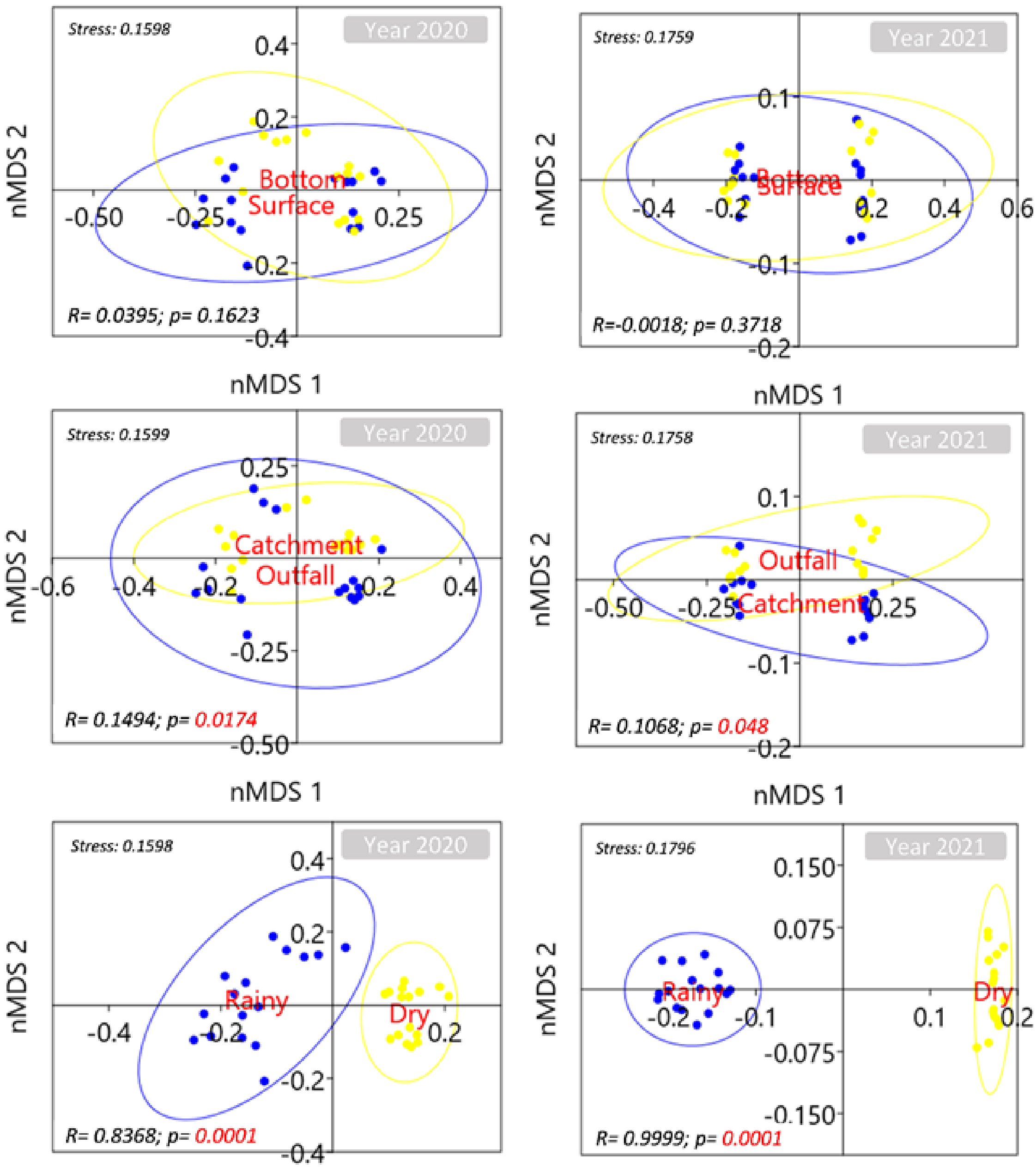


Figure 7- nMDS ordinate plots and ANOSIM test for the composition of the phytoplankton community in the area where the desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). Factors: spatial (catchment x outfall); vertical (subsurface x bottom) and seasonal (rainy x dry) and their respective sampling years. The Bray-Curtis index was used , and the significance level was 0.05. Values in red indicate significant differences ($p < 0.05$) (ANOSIM). Ellipses contain units that do not differ in composition within the 95% confidence interval. Catchment, subsurface and rainy areas are represented by blue; yellow ones represent outfall, bottom and dry.

3.2 Environmental variables and phytoplankton.

With regard to the physical and chemical parameters, the greatest variations were observed in 2020 (ΔpH= 0.74; ΔSalinity= 1.2; ΔChlorophyll= 0.412 µg.L-¹; ΔTotal suspended solids= 4.8 mg.L-¹), except for conductivity (Δ= 1,936 µS.cm-¹) and temperature (Δ= 1.5 ºC), where the greatest variations were observed in 2021. Table 2 shows the minimum and maximum values for each environmental variable, as well as the parameter variation values.

Table 2- Minimum and maximum values of environmental variables during the years 2020 and 2021 at the future desalination plant area, at Praia do Futuro (Fortaleza, Brazil). Average values with standard deviation. Δ= Variation of the environmental parameters between the maximum and minimum values of the sampling stations.

	2020			2021		
	Minimum	Maximum	Δ	Minimum	Maximum	Δ
Conductivity (µS.cm-¹)	(CSJa) 58,937 ± 87	(OBNo) 60,429 ± 65	1,492	(CSJu) 58,820 ± 120	(OSFe) 60,756 ± 72	1,936
pH	(CSJa) 8.07 ± 0.01	(CBNo) 8.81 ± 0.10	0.740	(CSFe) 8.34 ± 0.33	(OBJu) 8.81 ± 0.02	0.470
Temperature (ºC)	(OSNo) 28.52 ± 0.05	(CBJa) 29.13 ± 0.01	0.610	(CSJu) 27.4 ± 0.10	(OSFe) 28.9 ± 0.36	1.500
Salinity	(CSJa) 36.3 ± 0.05	(OBNo) 37.5 ± 0.03	1.200	(CSFe) 37.02 ± 0.41	(OBFe) 37.51 ± 0.01	0.490
Chlorophyll-a (µg.L-¹)	(OSJa) 0.235 ± 0.087	(OBNo) 0.647 ± 0.109	0.412	(CSFe) 0.129 ± 0.017	(OBJu) 0.343 ± 0.070	0.214
Total suspended solids (mg.L-¹)	(CSNo) 9.63 ± 0.97	(OBNo) 14.43 ± 1.32	4.800	(CSFe) 11.96 ± 5.0	(OBJu) 12.84 ± 2.12	0.880

Principal component analysis (PCA) explained 62.22% of the data variation and revealed that temperature was the parameter that best explained the variations in environmental data and that the rainy season stations were positively related to this parameter, as well as conductivity and total suspended solids. On the other hand, parameters such as salinity, pH and chlorophyll-a concentration were related to the dry season sampling stations (Figure 8).

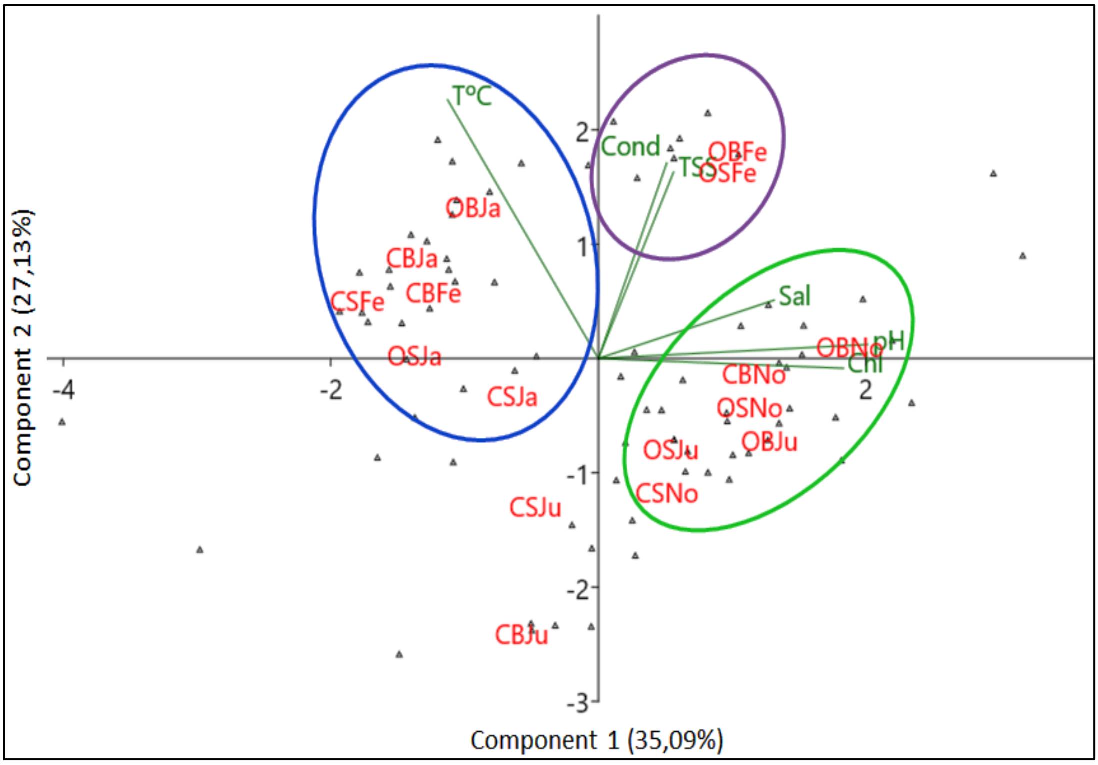


Figure 8- Biplot of principal components (PCA) between environmental variables and sampling points in 2020 (Rainy= CSJa, CBJa, OSJa, OBJa/ Dry= CSNo, CBNo, OSNo, OBNo) and 2021 (Rainy= CSFe, CBFe, OSFe, OBFe/ Dry= CSJu, CBJu, OSJu, OBJu), in the area of influence of the future desalination plant, Praia do Futuro (Fortaleza, Brazil). Environmental variables and their highest correlation coefficients, with the respective principal components (PC1 and PC2): (Cond) = conductivity: 0.516 (PC2); (pH) = hydrogen potential: 0.607 (PC1); (TºC) = temperature: 0.682 (PC2); (Sal) = salinity: 0.396 (PC1); (Chl) = chlorophyll-a: 0.552 (PC1); (TSS) = total suspended solids: 0.491 (PC2).

The results of the canonical correspondence analysis (CCA) for the relationship between the fifteen most representative taxa of the phytoplankton community and the environmental variables explained 86.01% (axis 1 and 2) and 90.44% (axis 1 and 2) of the total variability of the data, for the years 2020 and 2021, respectively. In 2020, the temperature variable had a greater influence on the data set and two harmful species had positive correlations with this parameter: 4- *Prorocentrum micans* and 12- *Chaetoceros* spp., while the harmful cyanobacterium 1- *Trichodesmium erythraeum* was negatively correlated with this variable and positively correlated with pH and salinity (Figure 9a). For 2021, the variables temperature and conductivity proved to be important for the data as a whole and the harmful species 2-*Gyrodinium* spp. was inversely related to these factors, but positively related to chlorophyll-a (Figure 9b). The correlation coefficients of the axes (1 and 2) are described in Table 3.

Table 3- Values of the correlation coefficients of the environmental variables of the first two axes of the canonical correspondence analysis (CCA) for the years 2020 and 2021 of the region where a desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). Environmental variables: conductivity; pH; temperature; salinity; chlorophyll-a; total suspended solids.

	2020		2021	
	Axis 1	Axis 2	Axis 1	Axis 2
Conductivity	-0.251646	-0.408184	-0.843643	0.168346
pH	-0.794821	-0.124193	0.0404717	0.350772
Temperature	0.838185	-0.302466	-0.928484	-0.010601
Salinity	-0.546074	-0.278354	-0.0467315	0.327282
Chlorophyll-a	-0.40051	0.232042	0.013736	-0.115783
Total suspended solids	-0.150154	-0.11098	-0.282367	-0.0319393

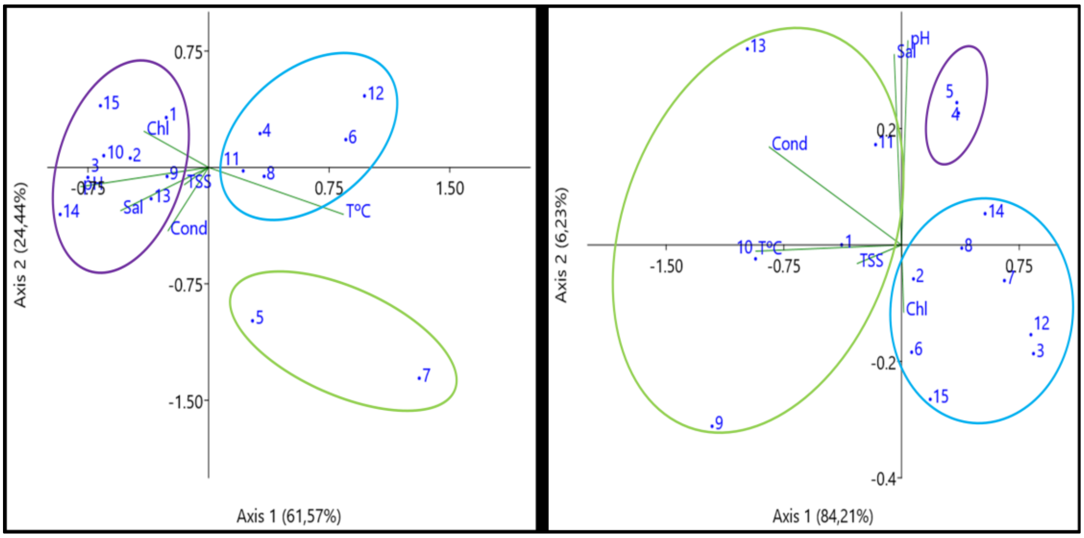


Figure 9- Ordination diagram with the results of the canonical correspondence analysis (CCA) based on the fifteen most representative phytoplankton taxa and associated environmental variables for each year of the study (Figure 8a = 2020 and Figure 8b = 2021) in the region where the desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). Figure 8a: Fifteen most representative taxa in 2020: 1- *Trichodesmium erythraeum* *; 2-Gymnodiniales spp. (10-20 µm); 3-Peridiniales spp. (10-20 µm); 4- *Prorocentrum micans**; 5- Pennates spp. (20-40 µm); 6-*Hemiaulus sinensis*; 7-*Hemiaulus* sp. ; 8- *Proboscia alata*; 9- *Rhizosolenia setigera*; 10-*Thalassionema* sp.;11- *Protoperidinium* spp.; 12- *Chaetoceros* spp.*; 13- *Cylindrotheca cf. closterium*; 14- Pennatess spp. (160-180 µm); 15- *Paralia sulcata*. Figure 8b: Fifteen most representative taxa in 2021: 1-Gymnodiniales spp. (10 - 20 µm); 2-*Gyrodinium* spp.*; 3-Peridiniales spp. (< 10µm); 4- Peridiniales spp. (10-20 µm); 5- *Cocconeis* spp. ; 6- *Cylindrotheca cf. closterium*;7- Penadas spp (10-20 µm); 8- Penadas spp. (20-40 µm); 9- *Hemiaulus membranaceus*; 10- *Proboscia alata*; 11- Peridiniales spp. (20 - 40 µm); 12- Penadas spp. (40-60 µm); 13- *Hemiaulus sinensis*; 14- Paralia sulcata; 15- *Pleurosigma* sp./ *Gyrosigma* sp. Environmental variables: (Cond) = conductivity; (pH) = hydrogen potential; (T°C) = temperature; (Sal) = salinity; (Chl) = chlorophyll; (TSS) = total suspended solids. Asterisk (*) indicates harmful algae.

4. Discussion

Our results showed that the phytoplankton composition was dominated by the diatoms and the highest significant densities were observed at the catchment point of the future desalination plant area in Praia do Futuro (Fortaleza, Brazil). Seasonal variations caused the greatest significant differences between the descriptors (richness, diversity, and density), with diversity displaying the smallest variations, which indicates a certain homogeneous distribution of species between the sampling points. Temperature proved to be an important parameter in explaining the variation of the community, as well as pH and conductivity. Four harmful species were among the fifteen most representative species (*Trichodesmium erythraeum* (cyanobacterium), *Chaetoceros* spp. (diatoms), *Prorocentrum micans* and *Gyrodinium* spp. (dinoflagellates) and were directly or inversely related to these variables. The cyanobacterium species *T. erythraeum* was the one that most caught our attention, as it is known to cause large harmful algal blooms (HABs) and produce toxins that are harmful to human health (D'SILVA et al., 2012; DETONI et al., 2016). However, its densities were relatively low when compared to other coastal regions (LENES et al., 2016; RODIER and BORGNE, 2008, JIANG et al., 2017). Our study constitutes an unprecedented baseline for assessing changes in the community, as well as the impacts of harmful species on the water itself to be generated in the area, which will harbor the future seawater desalination plant.

4.1 Composition of the phytoplankton community

The marine environment has its own peculiarities with regard to the composition and dynamics of the phytoplankton community. Some groups are the most representative in the marine phytoplankton, such as haptophytes, diatoms, and dinoflagellates (SACHITHANANDAM et al., 2022; SIMON, et al., 2009), and these last two groups were very representative in this study.

With regard to density, the highest averages were observed for the stations furthest from the coast (catchment), leading to a significant ($p<0.05$) spatial difference in relation to the future effluent emission area. This pattern may be related to the amount of suspended solids (TSS) at the points near the coast (emission area), as this variable can increase turbidity and interfere with the penetration of light into the water column (VILLA et al., 2019), dispersing or absorbing light radiation, negatively impacting the photosynthetic process (LUCE et al., 2010). This hypothesis is corroborated by the higher significant concentrations (ANOVA; p= 0.0134) of total suspended solids (TSS) at the stations near the coast (Outfall= 12.8 ± 0.8 $mg.L^{-1}$), when compared to more distant sampling stations (Catchment= 11.7 ± 0.9 $mg.L^{-1}$).

In addition to the higher TSS values near the coast, the mouth of the Cocó River is upstream of the study area, and can further increase TSS concentrations, especially during rainy periods, when there is a greater flow of the river into the sea, causing particulate matter to be carried away. In this context, the increase in TSS carried by the river and greater turbulence, coupled with low depths near the coastline, trigger the resuspension of sediment into the water column, affecting the penetration of radiation into the aquatic environment (OLIVEIRA et al., 2021).

Another condition that can interfere in the spatial variation of phytoplankton density is zooplankton herbivory, since along a coast-ocean gradient, zooplankton undergo changes in their concentration (individuals/m^3), increasing or decreasing the grazing pressure on phytoplankton (NEUMANN LEITÃO et al., 2019; BUENO et al., 2017). According to Gomes et al. (in preparation), the highest densities (ind./m^3) of zooplankton in the study region were observed for the points closest to the coast (outfall), which may generate greater grazing pressure on the phytoplankton community in this area.

In general, the highest values for richness, diversity and density were observed in the dry season, except for the CSJa station in the rainy season, where a bloom of the diatom *Chaetoceros* spp. caused an increase in organisms, raising the average abundance for the period. In addition, the significant differences in the descriptors were smaller between the sampling points in the dry period, and this homogeneity in the community may be related to little variation in environmental parameters, when compared to the rainy period, where there is a greater input of nutrients from rivers and rain galleries, in addition to the intrusion of estuarine species in the region (CARDOSO-MOHEDANO et al., 2022; SUN et al., 2020). Richness and diversity showed little variation, but were more influenced by seasonality, unlike density, where significant differences were more evident due to the spatial factor. The population balance of marine phytoplankton is a dynamic and complex process, where changes in the community are linked to abiotic and biotic factors, such as environmental variations, herbivory and interspecific interactions (SARKER et al., 2023; ZHENG et al., 2022; BURSON, et al., 2018; BOYD et al., 2010).

Variation in phytoplankton richness and diversity can be influenced by some specific factors, such as temperature, ammonia, and phosphate (PANJA et al., 2023; LEWANDOWSKA, et al., 2014). Seasonally, variations in certain environmental parameters are observed, and this process triggers changes in community structure (diversity and richness) (COSTA & CUTRIM, 2021; MUTTI, et al., 2020; DODDS, et al., 2019). Another factor that may interfere with the dynamics of species in the study region is the possible influence of taxa present in the plume of the Cocó River estuary, which may be driven to the sampling region by coastal drift currents influenced by seasonal winds, which intensify in the dry season, starting in the second half of the year.

Variations in species composition were more pronounced between the seasons (dry and rainy), as evidenced by the formation of groups in the cluster analysis and nMDS. During the survey it was also possible to observe a seasonal change in the dominant groups in 2021, where diatoms (20-200μm - microphytoplankton) were replaced by small dinoflagellates (2-20μm - nanophytoplankton). Many diatoms dominate more enriched environments, while dinoflagellates excel in oligotrophic conditions (BRUN et al., 2015; ALVES-DE-SOUZA et al., 2008) and changes in size are also associated with the nutritional conditions of the ecosystem, since larger cells dominate eutrophic environments and smaller ones are more representative in oligotrophic conditions, as they are more efficient at capturing nutrients (SOORIA et al., 2022). The change from microphytoplankton to nanophytoplankton took place in 2021, a year in which there was less rainfall, which leads us to believe that the environment received less nutrient input, due to lower river flows adjacent to the study area. In addition, nanophytoplankton had their highest densities in the dry season, a time with low nutrient input into the ecosystem.

4.2 Environmental variables and harmful algae.

Variations in physical and chemical parameters in marine environments can be influenced by both natural factors (e.g. wind and rain) (SARKER et al., 2023) and anthropogenic actions (e.g. effluent discharges) (TAYEB et al., 2015). The greatest variations between the environmental parameters analyzed were observed between the dry and rainy seasons, which indicates a seasonal influence on these oscillations. Changes in environmental variables affect the composition, distribution, and abundance of marine phytoplankton (JONKERS et al., 2019). The ordering of the sampling stations in the PCA analysis reinforces the influence of seasonality on environmental variables in the area of the future desalination plant.

The CCA analysis showed that temperature was the variable that best explained the variation in the data as a whole, along with pH and conductivity. Some phytoplankton taxa were related to these variables, directly or inversely, and some of them are considered harmful (HABs), such as *Trichodesmium erythraeum* (cyanobacteria), *Chaetoceros* spp. (diatoms), *Prorocentrum micans* and *Gyrodinium* spp. (dinoflagellates) (JYOTHIBABU et al., 2017; ESENKULOVA et al., 2022; LETERME et al., 2014; KIM, 2010; COSTA et al., 2005; PAULMIER, 1995). The occurrence of HABs has been a problem for several coastal regions around the world and in recent years the phenomenon has intensified both in frequency and in its geographical expansion, in addition to the emergence of new species causing HABs (ODUOR et al., 2023; YU ET AL., 2023; ANDERSON et al., 2021).

The species *Trichodesmium erythraeum* is a cosmopolitan taxon that proliferates on the surface of oligotrophic marine environments in tropical and subtropical regions (MCKINNA, 2015). This species is reported to form large harmful blooms all over the world (JYOTHIBABU et al., 2017; SABEUR et al., 2016; DETONI et al., 2016; KRISHNAN et al., 2007), generating biomass accumulation and causing the death of aquatic organisms by clogging the gills (D'SILVA et al., 2012). In addition, they are producers of potent toxins such as palytoxin and saxitoxin (DETONI et al., 2016, KERBRATE et al., 2011; PROENÇA et al., 2009), which can cause the death of aquatic organisms (NARAYANA et al., 2014; NEGRI et al., 2004) and even humans (PATOCKA et al., 2015; CUSICK & SAYLER, 2013). Its development occurs in waters with temperatures above 20 ºC, but other factors such as the availability of phosphorus, nitrogen and iron can contribute to its proliferation (COLUSSI et al.; 2024; LENES et al., 2008). The emergence of *T. erythraeum* blooms has already been related to temperature variations between 24 and 25 ºC and with decay between 25 and 26 ºC (LENES et al., 2016; RODIER & BORGNE, 2008). High correlation with high densities of *T. erythraeum* has already been reported for temperatures of 21.4 and 25.9 ºC and low correlation at 27.9 ºC (JIANG et al., 2017). Large blooms have been reported in less warm waters in the southwestern South Atlantic Ocean, with temperatures between 24 and 25.2 ºC (DETONI et al., 2016).

The highest concentrations of *T. erythraeum* were recorded in 2020, with the highest values for the dry period (745 ± 886 org./L) in a temperature of 28.5 ± 0.02 ºC; while the lowest densities were observed in the rainy period (281 ± 779 org./L) with a temperature of 29.0 ± 0.05 ºC. The inverse relationship between *T. erythraeum* and water temperature in this study suggests a certain limitation of growth at higher temperatures, but other factors need to be taken into account, such as the adaptations of populations to temperature variations, as well as the availability of some nutrients that limit their development in the area of the future desalination plant.

The diatom *Chaetoceros* spp. are not reported as producers of phycotoxins, but some species can generate ecological disturbances and deaths of aquatic organisms. These species have a wide distribution and are considered to be cosmopolitan and planktonic (ROUND et al., 1990). The harmfulness of *Chaetoceros* in marine ecosystems is reported for some species in blooms, such as *C. concavicornis* and *C. convolutus.* These species cause damage to the gills of fish, leaving them more susceptible to secondary bacterial infections, as well as hindering the diffusion of oxygen due to the accumulation of mucus in the respiratory epithelium (ESENKULOVA et al., 2022; LETERME et al., 2014; KUDELA et al., 2005; ALBRIGHT et al., 1993). In contrast, *C. muelleri* and *C. calcitrans* are commonly used as natural food in larvicultures of various species of aquatic animals (SOWASKE et al., 2023; DUY et al., 2017; SIRAKOV et al., 2015). Morphology is the main factor that enhances the harmfulness of some *Chaetoceros* species, as larger cells with large spicules (spines) at their ends cause mechanical damage to certain aquatic animals (TREASURER et al., 2003).

Other *Chaetoceros* species are also used as biological indicators, such as *C. tenuissimus*, which is indicated for biomonitoring chemical contaminants in marine environments (PASTORINO et al., 2022; SARKER et al., 2016). In this study, *Chaetoceros* spp. were directly influenced by temperature. *C. calcitrans* and *C. simplex* have already been reported to have their development favored by rising temperatures (KONG et al., 2021; HEMALATHA et al., 2012). The highest density of *Chaetoceros* spp. was recorded on the surface of the catchment in 2020, with an average value of 31,275 ± 19,488 org./L at a temperature of 28.9 ± 0.2 T ºC.

Dinoflagellates are very representative in marine environments and several species from this group are recognized as bloom-forming (TANG et al., 2023; SPRECHER et al., 2021). Among these species, *Gyrodinium* spp. and *Prorocentrum micans* stood out in this study. *Gyrodinium* spp. blooms have already been associated with fish mortality and deleterious effects on zooplankton, but the production of toxins is still unclear (KIM, 2010; COSTA et al., 2005; PAULMIER, 1995). The most obvious correlation of *Gyrodinium* spp. was inverse with the pH and salinity variables. Its highest densities were observed at the dry period catchment point in 2021, both in the subsurface (1,240 ± 605 org./L) and at the bottom (986± 371 org./L), and the related pH and salinity values were: 8.46 ± 0.04 and 37.24 ± 0.03, respectively. *Gyrodinium* is a heterotrophic dinoflagellate, and its proliferation may be related to the availability of prey in the region (LEE et al., 2022; BALLEN-SEGURA et al., 2017).

P. micans is a cosmopolitan species associated with blooms known as "red tide" in various parts of the world (PARK et al., 2013; YE et al., 2013; PENA-MANJARREZ et al., 2005; GÓMEZ, 2005), and has been reported to cause mortalities in molluscs (SHUMWAY, 1990; WANG et al., 1998). WANG et al. (2020) identified in *P. micans*, genes responsible for the synthesis of saxitoxin, a potent neurotoxin (PINTO et al., 2023), but did not detect the production of this compound. Other authors have not detected the presence of toxins in *P. micans* (PROENÇA et al, 1999; STEIDINGER & TANGEN, 1997), leading us to believe that the mechanism related to animal mortality is not clear for this species. Temperature and pH were the parameters that most explained the variations in the data, while temperature was positively correlated with *P. micans*, pH had an inverse relationship, which is corroborated by other authors, who observed this same trend (FATAH, et al., 2022; IBRAHIM et al., 2021; LI et al., 2011). Their highest densities were recorded in the rainy season catchment, ranging from 625 ± 443 org./L (subsurface) to 270 ± 87 org./L (bottom), with associated values of temperature= 29 ± 0.2 and pH= 8.1 ± 0.02.

5. Conclusions

Seasonal and spatial factors influenced the dynamics of the phytoplankton community and among the parameters analyzed, temperature proved to be the variable that best explained the changes in the community. All the harmful algae taxa recorded in this study can cause some damage to the marine ecosystem, however, *T. erythraeum* is the most worrying for the proper functioning of desalination plants, as it forms large algal blooms and can cause filters and membranes to clog, as well as producing potent toxins with a risk of problems for human health (JYOTHIBABU et al., 2017; DETONI et al., 2016). It is worth remembering that other harmful species were present during the evaluation, but in smaller quantities. Observing the variations in species dominance during the study period, it is possible that these less representative harmful algae stood out at some point, induced by environmental triggers in the region. In addition, the highest abundances were observed at the plant's water intake point, and this further reinforces the importance of periodic monitoring of these groups.

It should be noted that the highest densities found here are still an order of magnitude lower than values reported in oligotrophic marine waters (WANG et al., 2023; JIANG et al., 2022; VARKITZI et al., 2020), which characterizes the region as having low phytoplankton primary production. Finally, we hope that this work will be an important baseline research for future comparative assessments of the phytoplankton community during the operation of the desalination plant that will be installed in the study area and with other plants around the world.

6. References

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CHAPTER 3 – Diagnosis of the zooplankton community under the influence of a future large-scale desalination plant (Brazilian Semiarid Coast).

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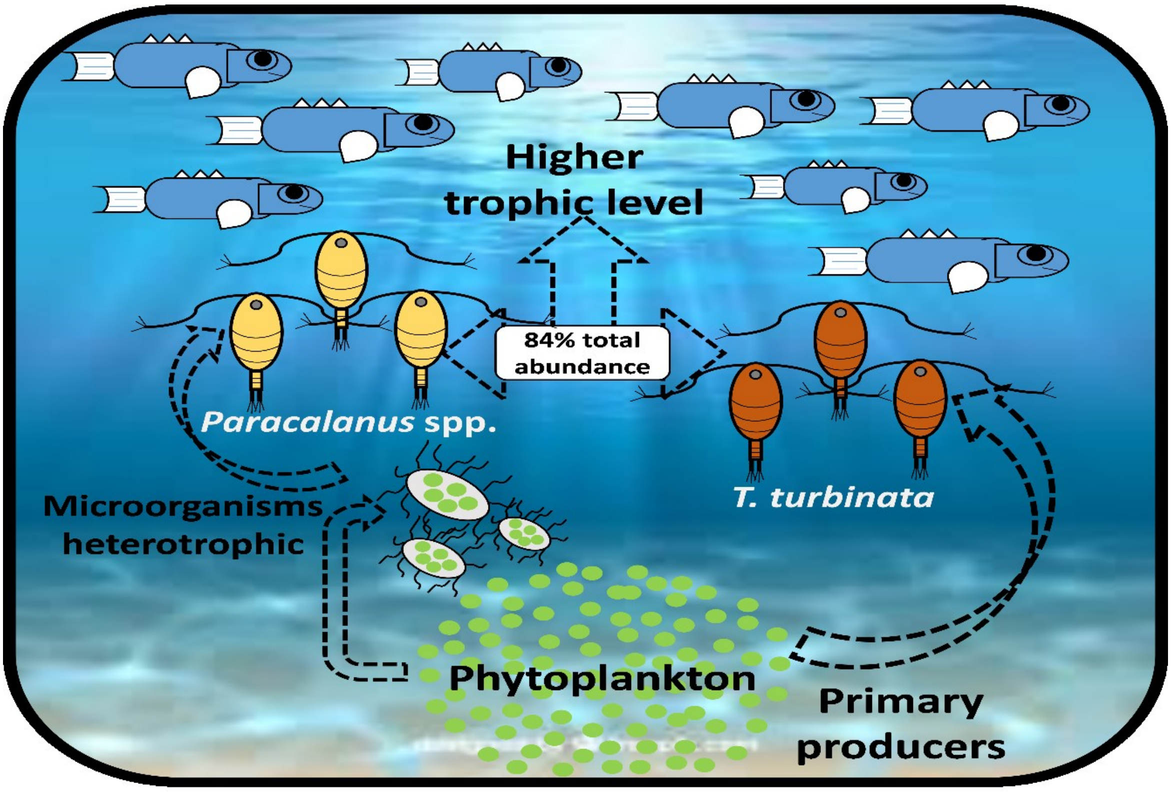
Abstract

Effluents from a seawater desalination plant can affect the biota of coastal ecosystems, especially the zooplankton community. This group is fundamental to marine environments, as it is a key group that sustains food chains, assists in nutrient cycling and is fundamental to the health and functioning of ecosystems. Changes in the structure of this community can impact its ecosystem function. The aim of this baseline study was assess the mesozooplankton in a region where a seawater desalination plant will be installed, located on Fortaleza, Brazilian semiarid coast. The results showed that the community was formed mainly by copepods, considering the total abundance of mesozooplankton. The species *Temora turbinata* (exotic species) and *Paracalanus* spp. dominated the community with the highest densities during the two analyzed years, suggesting that both are well adapted to the environmental conditions of the region. We found a high correlation between *T. turbinata* and chlorophyll-a concentrations. Other parameters such as dissolved oxygen, pH and temperature also indicated a correlation with these two abundant taxa. Given the influence of environmental parameters and the connectivity of photoautotrophic plankton organisms with relevant species in the region, we suggest long-term integrated monitoring of phytoplankton, zooplankton and environmental variables during the operation of the desalination plant. We hope that this baseline research will be an important database for comparative studies of impacts on mesozooplankton in the region under the influence of the largest plant to be installed in the Southwest Atlantic.

Keywords: Desalination; Mesozooplankton; Copepods; Environmental variables; Marine environment.

Graphical abstract



1. Introduction

The desalination of seawater consists of removing salts from the water through methods such as filtration or thermal processes, to obtain drinking water (TAN et al., 2020). This process also releases effluents with higher salinity and temperature compared to the environment, as well as different concentrations of chemical compounds (ROBERTS et al., 2010). Due to their physical and chemical characteristics that differ from the receiving environment, the disposal of desalination effluents (e.g. brine) causes concern regarding impacts on the ecosystem and marine animals, such as zooplankton (IHSANULLAH et al., 2021; BELKIN et al., 2017; MABROOK, 1994).

Zooplankton constitute a key group that sustains food chains and helps in nutrient cycling, being fundamental to the health and functioning of ecosystems (MONTEMEZZANI et al., 2015; KOSKI et al., 2020; TREBILCO et al., 2020). It is important to highlight the great role of zooplankton as an indicator of environmental conditions such as the impacts of construction in coastal regions (SOUZA et al., 2024). For example, the abundance, biomass, composition of some species and distribution patterns of zooplankton can indicate the degree of trophy of a given environment, as well as provide information on the structure of fish stocks (LI & CHEN, 2020; LOMARTIRE et al., 2021; BATCHELDER et al., 2013, LIU et al., 2014). Because they respond quickly to physical and chemical changes in the environment, zooplankton organisms have been increasingly used in environmental assessments of desalination plants (BATTEN et al., 2019; GOMES et al., 2023).

Some components of zooplankton are transient or permanent (STERNER, 2009). Transient zooplankton, known as meroplankton, are made up of larvae of benthic and nektonic organisms (HIDALGO et al., 2014). The permanent ones, known as holoplankton, include copepods, that are planktic for their entire life cycle. These small crustaceans often constitute the greatest diversity and biomass of mesozooplankton in marine environments (CARLOTTI et al., 2015; AMBRIZ-ARREOLA et al., 2018; BELTRÁN-CASTRO et al., 2020). Copepods play an important role in the efficiency of the biological pump, because through their excreta, they export carbon to deeper marine waters, effectively participating in the biogeochemical cycle of carbon in the oceans (COLE et al., 2016). In addition, many species are used as environmental bioindicators (TURNER, 2004; SILVA, 2011; PERBICHE-NEVES et al., 2016; SOARES et al., 2018; YI et al.; 2019; HAFEZ et al.; 2021).

Environmental stress caused by physical and chemical changes modifies the abundance and composition of the zooplankton community (HAYS et al., 2005; RICHARDSON, 2008, MACKAS et al., 2012, YEBRA et al., 2022). Variables such as temperature, turbidity, salinity, and dissolved oxygen directly affect these organisms (HUGGETT, 2014; BLANCO-BERCIAL et al., 2006; ISLAM, 2006; ANTON-PARDO & ARMENGOL, 2012; HE et al., 2021). Discharges from plants can be released into the marine environment with varying standards in physical and chemical parameters and this will depend on the methodology used to purify the water. For example, thermal desalination plants generate effluents with high temperatures when compared to the marine environment (LATTEMANN & HÖPNER, 2008) and this increase in temperature can benefit some thermotolerant zooplankton groups to the detriment of others that are less tolerant (SHI et al., 2020; YEBRA, et al., 2022). On the other hand, reverse osmosis plants discharge effluents with high concentrations of salts, causing an increase in this parameter at the point of influence of this discharge. It is known that salinity variation is an important mechanism for changes in aquatic communities, causing the disappearance of less tolerant species (GINATULLINA, et al., 2017; BRUCET et al. al., 2010). An increase in this variable can reduce species richness and diversity, affecting the structure of the zooplankton community (ANTON-PARDO & ARMENGOL, 2012; JENSEN et al., 2010; SCHALLENBERG et al., 2003).

In addition, both technologies (thermal and reverse osmosis) use chemical compounds during the desalination process and these compounds can reach the marine environment through the effluents, affecting zooplankton indirectly (SHARAFINIA et al., 2022; PANAGOPOULOS & HARALAMBOUS, 2020). An example is the use of iron hydroxide (coagulant), used in many desalination plants. This compound can cause a decrease in abundance and changes in the phytoplankton community (Belkin et al., 2017; Drami et al.; 2011). Consequently, as the primary consumer of phytoplankton, zooplankton are closely interconnected and end up being impacted by changes in the composition of their food resource (POMEROY et al., 1987).

Given the important ecological role of zooplankton in the marine environment, the possible environmental impacts of desalination plants and the size of the project, it is of fundamental importance to carry out a prior diagnosis of this community, since the lack of basic diagnoses makes it difficult to assess possible environmental impacts (CARMO et al., 2017; FERNANDES et al., 2016). The desalination plant that will be installed in the area of this study was designed to use reverse osmosis technology and the brine discharge will have a flow rate of 1.3 m^3/s, which will be discharged 1.2 km from the coast. This desalination plant will be the largest in Brazil and will have a treated water production capacity of 1.0 m^3/s and will supply 700,000 people (PEREIRA et al., 2021).

Considering the size of the project, the influence of desalination discharges on the environment and the marine biota, the aim of this study was to carry out a spatio-temporal assessment of the composition, richness, diversity and density of the zooplankton community, with an emphasis on copepod assemblages, in a region where a desalination plant will be installed at Praia do Futuro-CE, an urban sandy beach.

2. Materials and methods

2.1. Study area

The region sampled is located on Praia do Futuro beach, Fortaleza-CE, on a stretch of the semi-arid continental shelf in northeastern Brazil (MORAES et al., 2020). The region has oligotrophic characteristics (MORAES et al., 2020; EKAU & KNOPPERS, 1999), with two well-defined seasonal periods, the dry season and the rainy season. The rainy period is from January to May, while the dry period is from June to December (FUNCEME, 2023). Average temperatures vary between 24.5 ºC (average minimum temperature) and 31.0 ºC (average maximum temperature), while winds intensify between the months of July and November, with average magnitudes varying between 2.0 and 4.0 $m.s^{-1}$ (INMET, 2023). The region also has a strong hydrodynamic activity with a predominance of currents induced by westerly winds close to the coast (SOARES & CASTRO FILHO, 1996). It is a sandy urban beach with a high influx of visitors and is approximately 8km long, bordered by the Cocó River (southeast) and the Titã pier (northwest); with a meso-tidal regime and dissipative, intermediate and reflective morphodynamic characteristics (ALBUQUERQUE et al., 2010; SILVA et al., 2000).

The sampling grid was design according to the future installation of the desalination plant. The preliminary diagnosis consisted of a total of ten points parallel to the coastline, with five points closer to the coast called the saline effluent outfall (O1-O5) and five points further from the coast called the seawater intake (C1-C5) (Figure 1a). The distance between the intake and outfall points is approximately 1 km, and the study area is approximately 5km from the mouth of the Cóco River (Figure 1b).

The sampling stations were identified as follows: CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February 2021; OFeb/21= outfall February 2021.

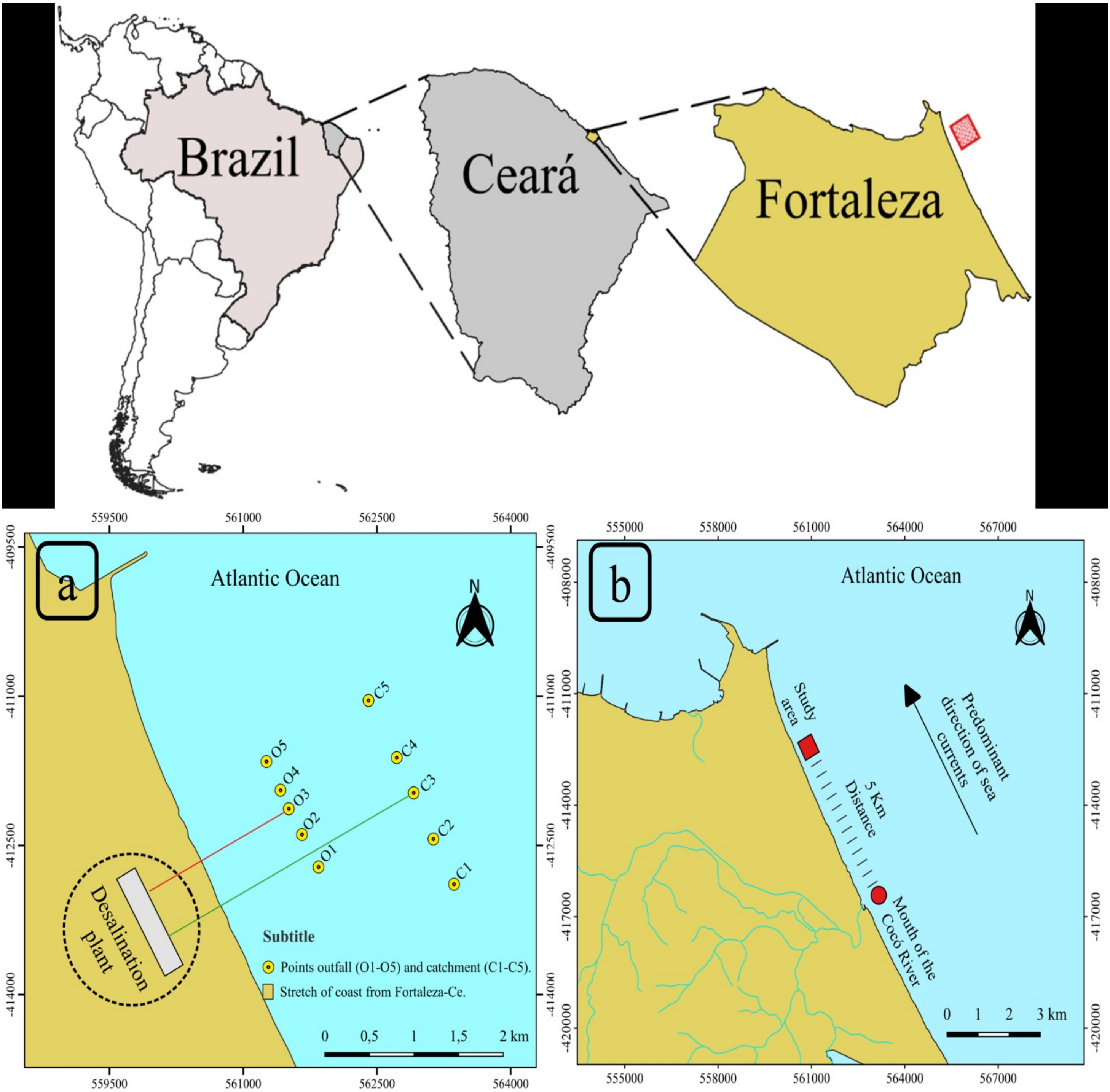


Figure 1- a) Location of the study area where the desalination plant will be installed on Praia do Futuro (Fortaleza, Brazil), with details of the sampling grid for the five catchment (C1-C5) and outfall (O1-O5) sampling points. b) Distance between the mouth of the Cocó River and the study area.

2.2 Sample collection and analysis

The subsuperficial samples were collected in two campaigns on board a motorized boat in January 2020 and February 2021, within the rainy season, totaling 20 samples. Each zooplankton sample was obtained by horizontal subsurface trawl, during five minutes. These trawls were carried out with a conical plankton net (200 µm), capturing the fraction known as mesozooplankton. The net was equipped with a General Oceanic flowmeter to measure the volume of water filtered. After the trawls, the samples were stored in plastic bottles and immediately fixed with a 4% formaldehyde solution buffered with sodium tetraborate (0.5 g/L). Samples for chlorophyll-a analysis were collected using a Van Dorn bottle and stored in 5 L bottles under refrigeration. The values of the environmental variables (pH, total suspended solids, salinity, temperature, and water transparency) were obtained in situ using a EXO2 multi-parameter probe (Yellow Springs Instruments (YSI), Brannum Lane, Ohio, USA) and water transparency was assessed using a Secchi disk.

In the laboratory, the samples were fractionated (fractionations ranged from 1/32 to 1/256) using a Motoda type sub-sampler (Omori and Ikeda, 1984). After obtaining the aliquots, all the zooplankton organisms present in the subsamples were counted under a stereomicroscope. The taxa were identified to the lowest possible taxonomic level. Cnidaria, Bryozoa, Annelida and Echinodermata had the lowest densities and relative abundances during the assessment of the zooplankton community and were therefore considered in the analysis in a single group called "Others". The copepod species were identified according to specialized literature (TREGOUBOFF and ROSE, 1957; BJÖRNBERG, 1981; BRADFORD-GRIEVE et al., 1999). Chlorophyll-a concentrations were analyzed following the methodology proposed by APHA, 1999.

The data used in this work were obtained from the project: Avaliação da variabilidade espaço temporal da qualidade da água e sedimento na praia do Futuro (Fortaleza-Ceará): um estudo anterior à construção da planta de dessalinização do estado do Ceará. (LABOMAR, 2022).

2.3 Statistical analysis of the data

The data was normalized with a square root transformation and to guarantee the same weight for all the physical and chemical variables, a "z-value" transformation was used. All the statistics were based on copepod species, as they are the most abundant group within the mesozooplankton community sampled, and the sampling effort was evaluated using a species accumulation curve.

With regard to diversity analyses, only Copepoda species were analyzed due to the difficulty in identifying the other groups down to the specific level. All Copepoda taxa were used in the analysis, including those with only one occurrence. Some copepods were not identified to the specific level due to their juvenile stage of development (such as *Oithona* spp. and *Labidocera* spp.) and due to difficulties related to identification. Individuals of the family Paracalanidae lost important appendages during the collection process or fixation with formaldehyde solution, which did not allow them to be identified to the specific level. The occurrence of the species *Parvocalanus crassirostris* (Dahl F., 1894), *Parvocalanus scotti* (Früchtl, 1923), *Paracalanus aculeatus* (Giesbrecht, 1888), and *Paracalanus indicus* (Wolfenden, 1905) is possible.

The Shannon-Wiener diversity index (H'), richness, density, equitability and species composition were used to assess the ecological patterns of the zooplankton community. Analyses of variance (ANOVA) followed by Tukey's test for multiple comparisons were carried out to check for significant ($p<0.05$) spatial and temporal differences in species diversity, richness, density, and evenness. Species composition was assessed using non-metric ANOSIM test, with a Bray-Curtis index and 9999 permutations. Hierarchical cluster analysis was carried out and the sampling stations were grouped according to the Bray-Curtis similarity index. The SIMPER test was also carried out to assess the contribution of the most important taxa to dissimilarity between groups.

Canonical correspondence analysis (CCA) was performed to explore correlations between copepods (the most abundant group) and environmental variables (pH, dissolved oxygen, salinity, total suspended solids, chlorophyll-a, water temperature, and transparency) and principal component analysis (PCA) was performed to obtain correlations between variables and collection stations. The statistical software package Paleontological Statistics (PAST 4.09) was used to carry out the statistical analyses.

3. Results

3.1 Structure of the zooplankton community.

During the study, taxa belonging to eight phyla were recorded: Cnidaria, Bryozoa, Chaetognatha, Mollusca, Annelida, Arthropoda, Echinodermata, and Chordata. Arthropods were very representative, comprising the highest relative abundances at both sampling stations (catchment and outfall), followed by Mollusca, Chordata, Chaetognatha and Others (Cnidaria, Bryozoa, Annelida and Echinodermata) (Figure 2).

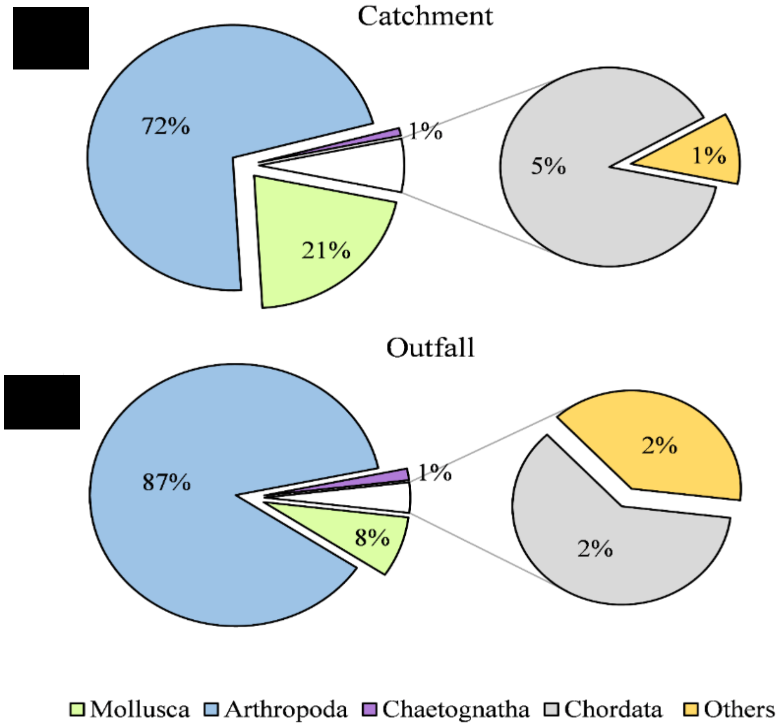


Figure 2- Relative abundance of the zooplankton community, highlighting the phyla Mollusca, Arthropoda, Chaetognatha and Others (Cnidaria, Bryozoa, Annelida and Echinodermata). (a) Catchment and (b) Outfall points of the area destined to receive the future desalination plant at Praia do Futuro (Fortaleza, Brazil).

The highest relative abundances were observed for holoplankton organisms, both in the catchment and in the outfall, where they contributed 73% and 90%, respectively (Figure 3a). Average densities between the catchment and outfall varied between 29.23 ± 11.85 ind./m³ and 70.47 ± 9.24 ind./m³ for holoplankton and between 8.25 ± 1.2 ind./m³ and 10.82 ± 5.47 ind./m³ for meroplankton, respectively (Figure 3b).

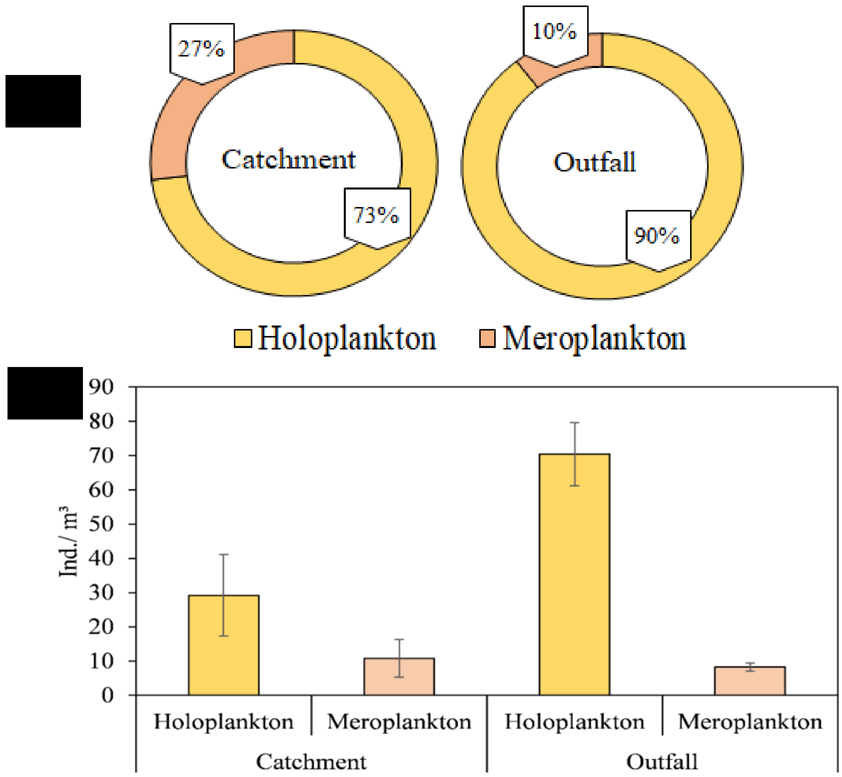


Figure 3- Relative abundance (a) and average densities (b) of holoplankton and meroplankton in Catchment and Outfall points of the area where the desalination plant will be installed at Praia do Futuro (Fortaleza, Brazil).

The meroplankton was composed primarily of larvae of the phyla Mollusca and Chordata, comprising around 85 % of the total abundance (Figure 4), with their densities varying significantly ($p< 0.05$; ANOVA) between the years 2020 (16 ± 8 ind./m^3) and 2021 (3 ± 1 ind./m^3). However, there was no significance between the catchment and outfall stations ($p> 0.05$; ANOVA).

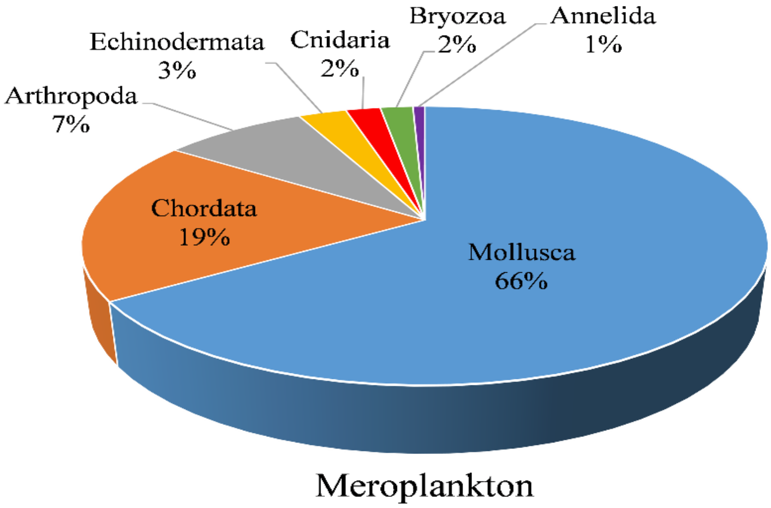


Figure 4- Relative abundance for the components of the meroplankton in the area where the desalination plant will be installed at Praia do Futuro (Fortaleza, Brazil).

The highest densities were recorded for the phylum Arthropoda with a minimum of 28.73 ± 11.73 ind./m³ (catchment) (Figure 5a), reaching a maximum of 68.76 ± 9.39 ind./m³ (outfall) (Figure 5b). The smallest contributions were made by the phyla Cnidaria, Bryozoa, Annelida and Echinodermata (Others), which together showed average densities of 0.30 ± 0.13 ind./m³ (catchment) (Figure 5a) and 1.14 ± 0.58 ind./m³ (outfall) (Figure 5b). The copepods stood out with the highest concentrations ranging from 27.29 ± 20.47 ind./m³ (catchment) (Figure 5a) to 64.89 ± 36.67 ind./m³ (outfall) (Figure 5b), characterizing the greatest increase in relative abundance in the phylum Arthropoda.

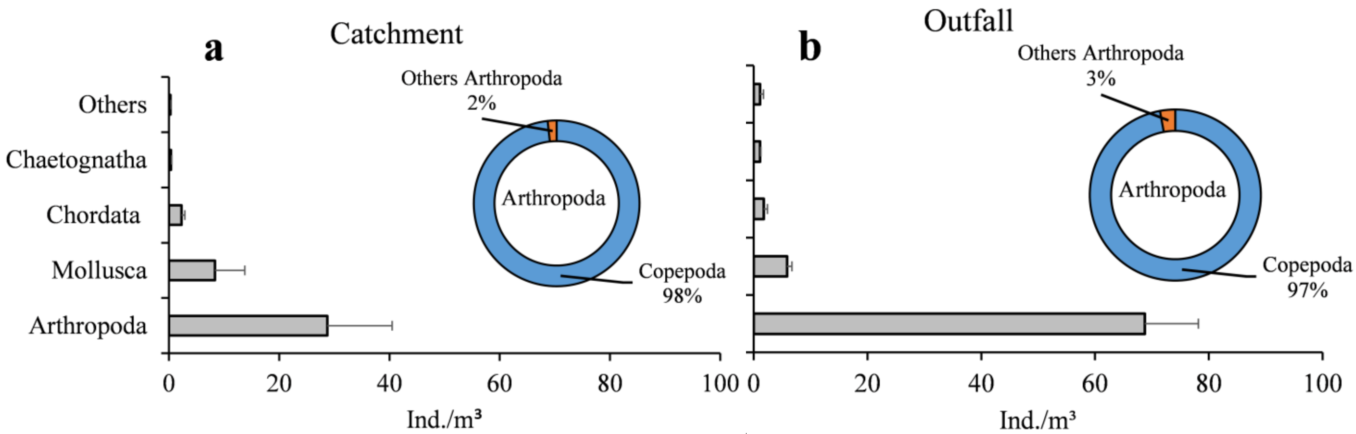


Figure 5- Average density (ind./m³) for each phylum and relative abundance of copepods in the Phylum Arthropoda in the area where the desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). a) Catchment; b) Outfall.

Analyzing only Copepoda species, the species accumulation curve showed a stabilization of the curve, indicating that the sampling effort was sufficient to describe the diversity of this group in the study region (Figure 6).

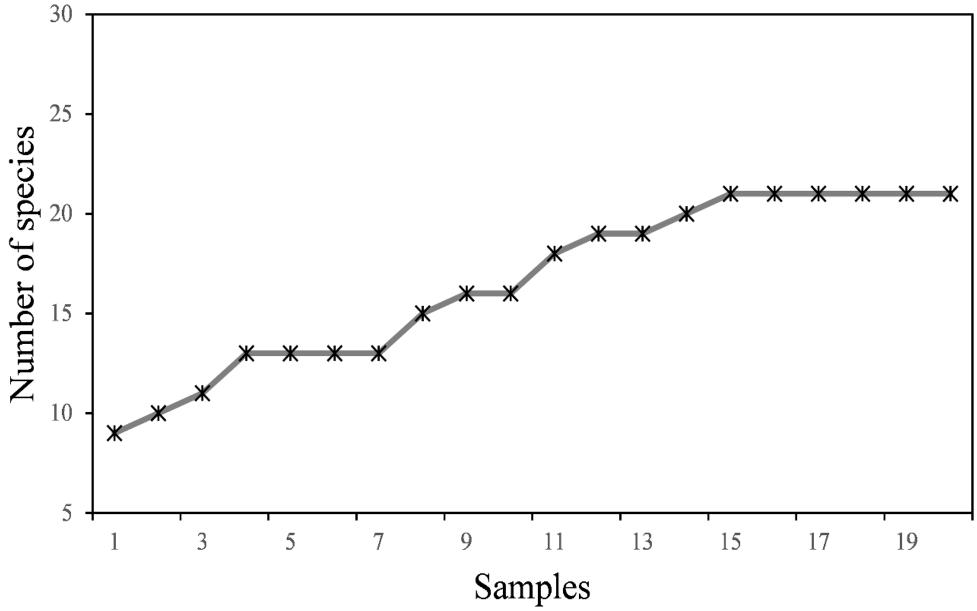


Figure 6- Accumulation curve of Copepoda species in the area where the desalination plant will be installed in Paria do Futuro (Fortaleza, Brazil).

During the survey, 19 copepod taxa were catalogued, distributed in three orders: Calanoida (9 taxa), Cyclopoida (8 taxa) and Harpacticoida (2 taxa) (Table 1).

Table 1- Copepod taxa identified during the evaluation and their respective orders.

Taxa	Order
Acartia (Odontacartia) lilljeborgi (Giesbrecht, 1889)	Calanoid
Calanopia americana (Dahl F., 1894)	Calanoid
Centropages velificatus (Oliveira, 1947)	Calanoid
Paracalanus spp.	Calanoid
Temora turbinata (Dana, 1849) – exotic species	Calanoid
Temora stylifera (Dana, 1849)	Calanoid
Labidocera spp.	Calanoid
Clausocalanus furcatus (Brady, 1883)	Calanoid
Undinula vulgaris (Dana, 1849)	Calanoid
Corycaeus spp.	Cyclopoid

Corycaeus giesbrechti (Dahl F., 1894)	Cyclopoid
Corycaeus amazonicus (Dahl F., 1894)	Cyclopoid
Oithona hebes (Giesbrecht, 1891)	Cyclopoid
Oithona nana (Giesbrecht, 1893)	Cyclopoid
Oithona spp.	Cyclopoid
Farranula sp. (Wilson C.B., 1932)	Cyclopoid
Farranula gracilis (Dana, 1849)	Cyclopoid
Euterpina acutifrons (Dana, 1847)	Harpacticoid
Macrosetella gracilis (Dana, 1846)	Harpacticoid

The spatial variation (catchment x outfall) affected all descriptors except for richness. On the other hand, for the temporal aspect (2020 x 2021), all the descriptions assessed (richness, diversity, equitability and density) were significant ($p < 0.05$; ANOVA) (Table 2).

Table 2- Analysis of variance (ANOVA) for richness, diversity, equitability, and density of copepod assemblages in the area where the desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). Evaluation of the significance of spatial and temporal factors for each community descriptor. ($p<0.05$ was highlighted in red)

	Richness		Diversity		Equitability		Density	
Factors	F	*p*	F	*p*	F	*p*	F	*p*
Spatial (catchment x outfall)	0,4348	0,519	11,64	0,003574	20,6	0,000336	35,21	2,10E-05
Temporal (Interannual)	48,85	3,05E-06	87,47	6,91E-08	67,42	3,95E-07	64,04	5,53E-07

The highest values for richness, diversity and evenness were observed in 2021, with no significant difference ($p < 0.05$; Tukey) between the catchment and the outfall (Figure 7). In 2020, diversity and evenness differed between catchment and outfall. With regard to density, the highest values were observed in 2020, where a significant difference ($p < 0.05$; Tukey) could be seen between the catchment and the outfall (Figure 7).

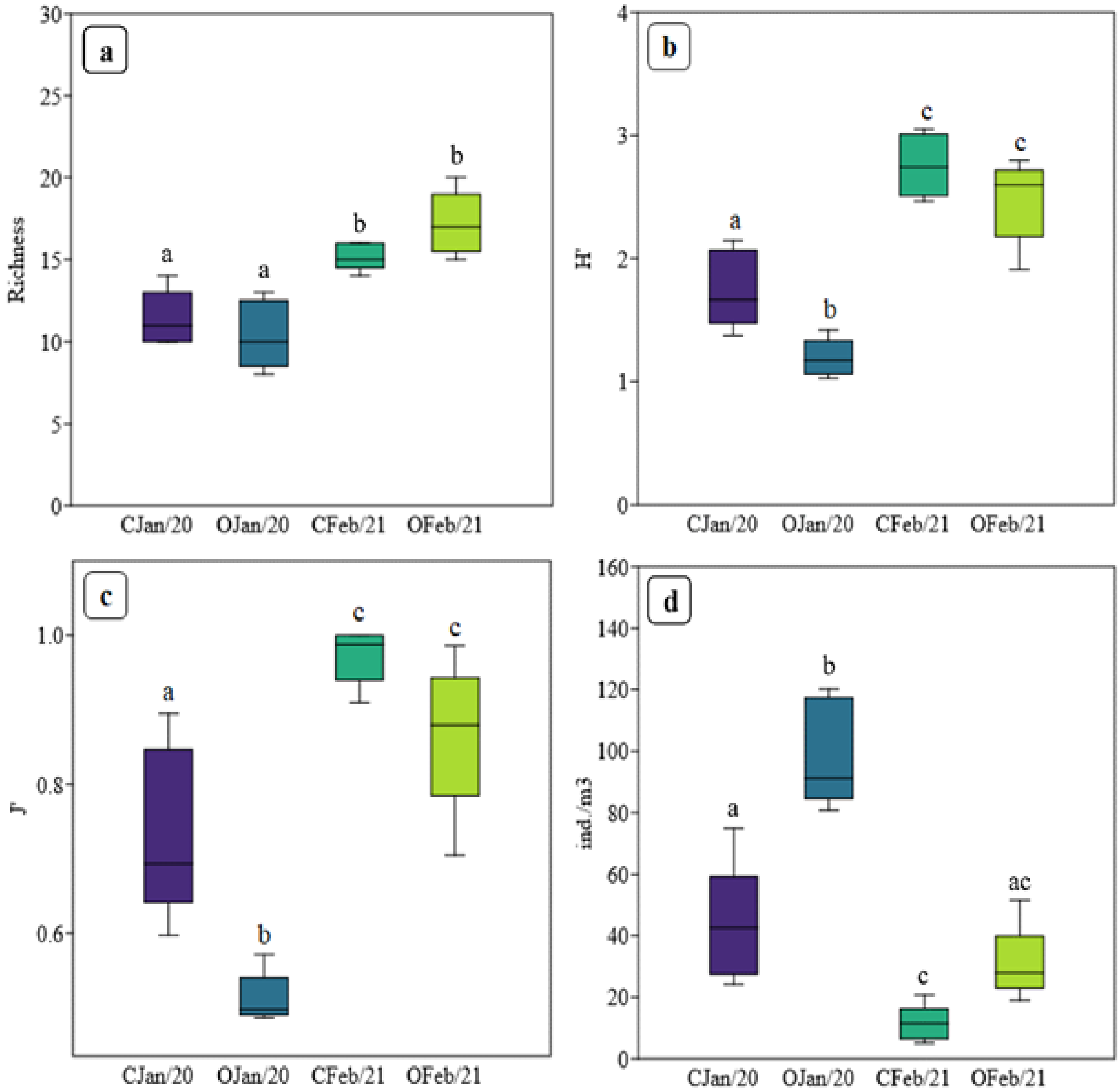


Figure 7 - Boxplots comparing copepod richness (a), diversity (b), evenness (c) and density (d) between the sampling stations in the region where the desalination plant will be installed, Praia do Futuro (Fortaleza, Brazil). CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February 2021; OFeb/21= outfall February 2021. Different letters above the boxplots show significant differences ($p<0.05$, Tukey).

The cluster analysis based on the copepod assemblages showed the formation of four main groups (Figure 8). It is possible to see a clear formation of groups with spatial (catchment and outfall) as well as temporal distinctions. Group (A) was formed by outfall stations from the year 2021, group (B) by outfall stations from 2020, with one of the catchment stations from the same year included in the group. Groups (C) and (D) were made up of catchment stations from 2020 and 2021, respectively. The SIMPER test showed that the species *T. turbinata* and *Paracalanus* spp. contributed mostly to the dissimilarity between the groups, followed by *Calanopia americana*, *Corycaeus amazonicus*, *Corycaeus* spp. and *Farranula* sp. (Figure 8).

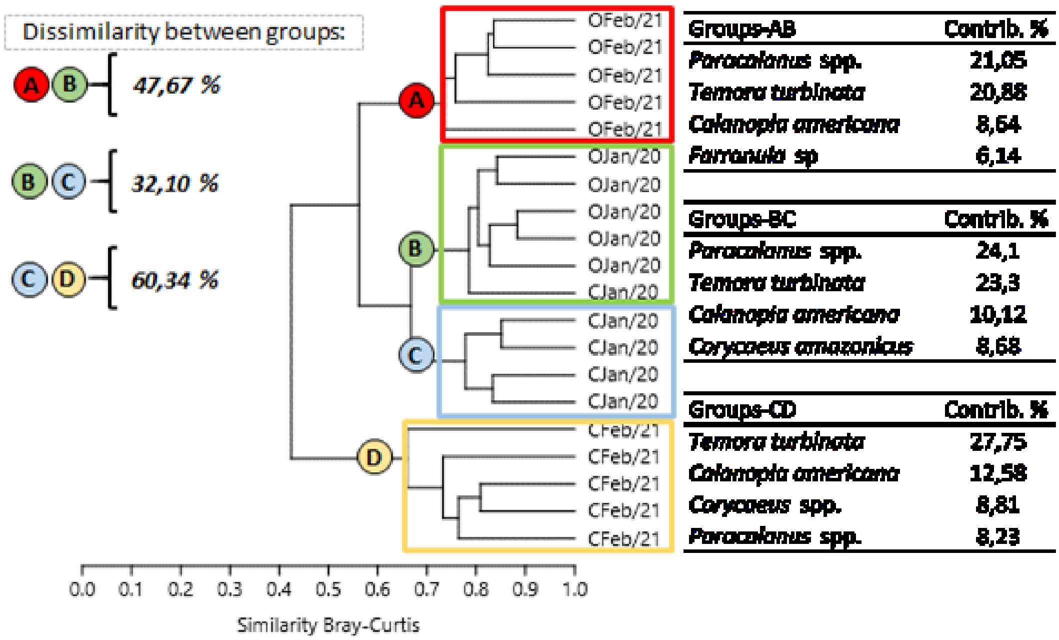


Figure 8- Similarity dendrogram (Bray-Curtis) and SIMPER test between the sampling stations (CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February 2021; OFeb/21= outfall February 2021) based on copepod abundances in the region where the desalination plant will be installed at Praia do Futuro (NE, Brazil). Groups formed are indicated with the letters A, B, C and D.

The nMDS analysis followed by the ANOSIM test showed a significant difference in species composition, both for the spatial factor (catchment x outfall) and the temporal factor (rainy x dry) (Figure 9). The replacement of dominant species was not observed in this study and the taxa that dominated the copepod community were *Paracalanus* spp. with average densities between 7.17 ±2.91 ind./m³ (2021) and 27.10 ± 16.64 ind./m³

(2020), as well as *Temora turbinata* with averages between 6.85 ±8.37 ind./m³ (2021) and 35.65 ±1 6.82 ind./m³ (2020).

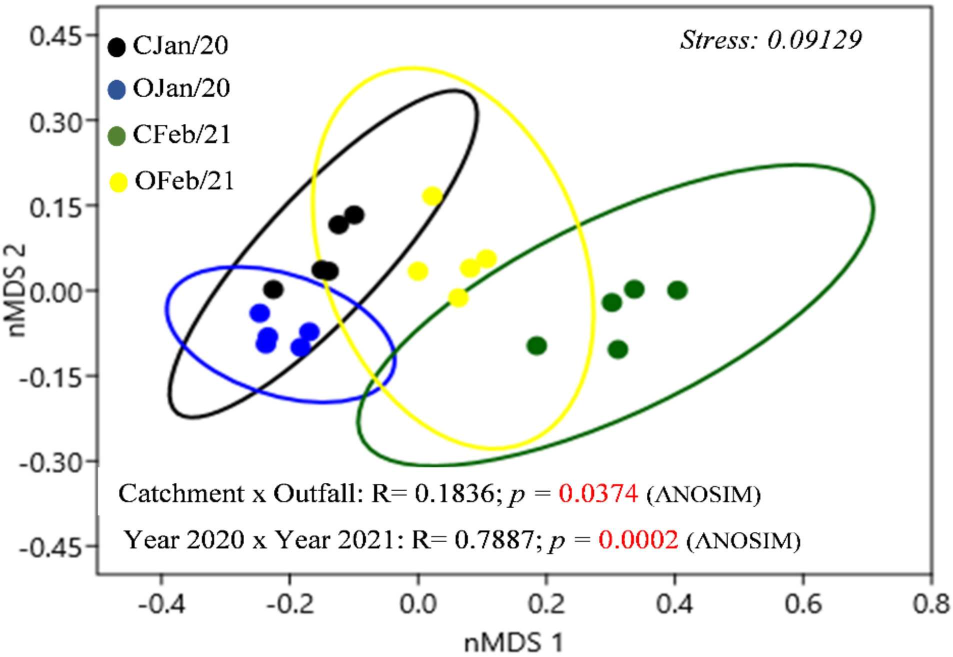


Figure 9- nMDS ordination plots and ANOSIM test for the composition of copepods between catchment x outfall (spatial) and between the years 2020 x 2021 (temporal) in the region where the desalination plant will be installed, Praia do Futuro (NE, Brazil). Bray-Curtis index and 0.05 significance level. Values in red indicate significant differences ($p < 0.05$; ANOSIM). Ellipses contain units that do not differ in composition within the 95% confidence interval. CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February 2021; OFeb/21= outfall February 2021.

3.2 Copepod assemblages and environmental variables

Evaluating the physical and chemical parameters, in general, the smallest variations between the minimum and maximum values were recorded for temperature, dissolved oxygen and total suspended solids, while pH, salinity, chlorophyll-a and water transparency had the greatest significant variations ($p< 0.05$; ANOVA) between the minimum and maximum values (Table 3). In January 2020, the month in which the rainy season campaign was carried out, 14 mm of precipitation was recorded, while the campaign carried out in February 2021 had a monthly accumulation of 65 mm of precipitation. Considering the annual rainfall, it can be seen that 2020 (1,888 mm) was wetter than 2021 (1,281 mm) (FUNCEME). The time factor (2020 x 2021) caused the greatest significant variations ($p < 0.05$; ANOVA) in the environmental parameters, with the exception of dissolved oxygen, temperature and total suspended solids (Table 4).

Table 3- Environmental variables assessed with their respective sampling stations and variations between minimum and maximum values (Δ) in the region where a desalination plant will be installed on Futuro beach (NE, Brazil). (*) Asterisk identifies significant difference (ANOVA; $p < 0.05$). CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February.

	Minimum	Maximum	Δ
Salinity	(CJan/20)	(OFeb/21)	1.370*
	36.290 ± 0.050	37.660 ± 0.320	
pH	(CJan/20)	(OFeb/21)	0.660*
	8.070 ± 0.010	8.730 ± 0.050	
Temperature -ºC	(CFeb/21)	(OJan/20)	0.360
	28.53 ± 0.340	28.890 ± 0.250	
Dissolved oxygen (mg.L^{-1})	(OJan/20))	(OFeb/21)	0.320
	7.000 ± 0.100	7.320 ± 0.630	
Chlorophyll -a (µg.L^{-1})	(CFeb/21)	(CJan/20)	0.385*
	0.138 ± 0.010	0.523 ± 0.190	
Total suspended solids (mg/L)	(OJan/20)	(CFeb/21)	2.840
	11.080 ± 0.270	13.920 ± 5.020	
Water transparency	(OFeb/21)	(OJan/20)	6.620*
	5.800 ± 0.240	12.420 ± 1.320	

Table 4- Evaluation of the spatial (catchment x outfall) and temporal (interannual) variation of environmental variables in the area of the future desalination plant at Praia do Futuro (NE, Brazil). In red are significantly different values ($p<0.05$; ANOVA).

	Spatial		Temporal	
	F	*p*	F	*p*
Salinity	8.848	0.00894	45.97	4.42E-06
pH	13.99	0.001783	13.28	0.002188
Temperature	0,6597	0.4286	2.771	0.1154
Dissolved oxygen (mg.L^{-1})	1.75E-05	0.9967	0.3308	0.5732
Chlorophyll-a (µg.L^{-1})	0.09164	0.766	10.86	0.004568
Total suspended solids(mg/L)	0.2027	0.6586	2.063	0.1702
Transparency	0.05224	0.8221	45.74	4.55E-06

The principal component analysis (PCA) revealed that the 2020 sampling stations were more associated with temperature, Secchi and chlorophyll-a values. For 2021, the stations were associated with pH and salinity (Figure 10). The first two principal components (PC) together explained 56.62% of the variations in the data, and the parameters that had the most influence on the data set were: chlorophyll-a, dissolved oxygen, and salinity.

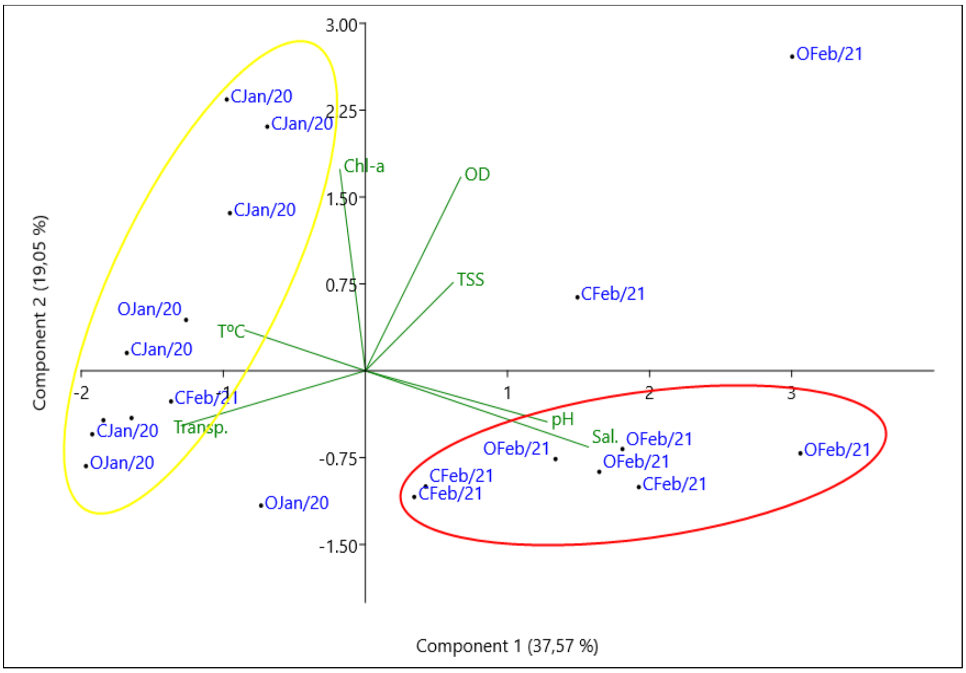


Figure 10- Biplot of the principal component analysis (PCA) between environmental variables and sampling stations (CJan/20 = catchment January 2020; OJan/20 = outfall January 2020; CFeb/21= catchment February 2021; OFeb/21= outfall February 2021) in the area of influence of the desalination plant, Praia do Futuro (NE, Brazil). Environmental variables and their highest correlation coefficients, with the respective principal components (PC1 and PC2): (DO) = dissolved oxygen: 0.616 (PC2); (pH) = hydrogen potential: 0.47123 (PC1); (T°C) = temperature: 0.31301 (PC1); (Sal) = salinity: 0.57839 (PC1); (Chl) = chlorophyll-a: 0.63995 (PC2); (TSS) = total suspended solids: 0.28071 (PC2); water transparency: 0.4776 (PC1).

The results of the canonical correspondence analysis (CCA) for the relationship between the ten most representative copepod taxa and the environmental variables explained 90.31% (axis 1 and 2) of the total variability of the data (Figure 11). The variables chlorophyll-a, dissolved oxygen and water transparency had the greatest influence on the variability of the copepod taxa and their correlation coefficients are shown in Table 5. The ten most representative species during the study were : *Calanopia americana*; *Centropages velificatus*; *Corycaeus* spp.; *Corycaeus amazonicus*; *Paracalanus* spp.; *Temora turbinata*; *Temora stylifera*; *Labidocera* spp.; *Farranula* sp.; *Undinula vulgaris*.

Temora turbinata and *Labidocera* spp. correlated with chlorophyll-a, temperature, and dissolved oxygen. *Calanopia americana* and *Corycaeus amazonicus* were more closely related to oxygen and pH. *Paracalanus* spp. and *Undinula vulgaris* were negatively correlated with pH and dissolved oxygen. *Temora stylifera* was correlated with total suspended solids and salinity. *Farranula* sp. and *Corycaeus* spp. were not correlated with the variables that were measured.

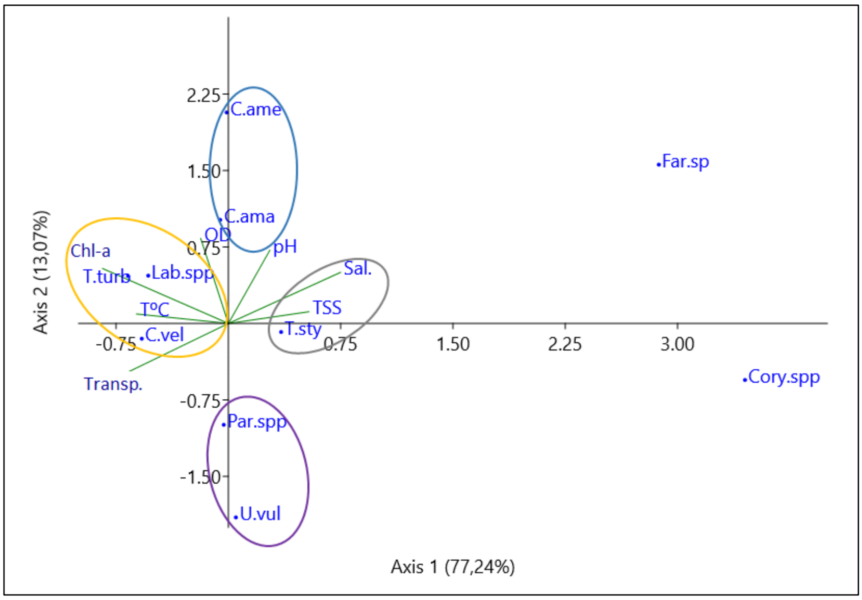


Figure 11- Ordination diagram with the results of the canonical correspondence analysis (CCA) based on the ten most representative copepod taxa and environmental variables in the area where the desalination plant will be installed, Praia do Futuro (NE, Brazil). Representative species: *Calanopia americana* (C.ame); *Centropages velificatus* (C.vel); *Corycaeus* spp. (Cory.spp); *Corycaeus amazonicus* (C.ama); *Paracalanus* spp. (Par.spp); *Temora turbinata* (T.turb); *Temora stylifera* (T.sty); *Labidocera* spp. (Lab.spp); *Farranula* sp. (Far.sp); *Undinula vulgaris* (U.vul). Environmental variables: (Cond) = conductivity; (pH) = hydrogen potential; (TºC) = temperature; (Sal) = salinity; (Chl-a) = chlorophyll-a; (TSS) = total suspended solids; water transparency = (Transp.).

Table 5 - Correlation coefficients of the environmental variables for the first two axes of the canonical correspondence analysis (CCA) based on the most representative taxa of the copepod assemblages in the area where the desalination plant will be installed on Praia do Futuro (Fortaleza, Brazil). Environmental variables: dissolved oxygen; pH; temperature; salinity; chlorophyll-a; total suspended solids and water transparency.

Parameters	Axis 1	Axis 2
pH	0.184633	0.478777
Dissolved oxygen	-0.123153	0.555557
Temperature	-0.408672	0.0617697
Salinity	0.499395	0.334078
Chlorophyll-a	-0.560014	0.359271
Total suspended solids	0.358562	0.0766755
Transparence water	-0.538555	-0.383094

4. Discussion

We assessed the structure of the zooplankton community with a focus on copepod assemblages in a region of Praia do Futuro (NE, Brazil) where a seawater desalination plant will be installed. The results showed the dominance of holoplanktonic organisms over the total density of zooplankton, with the copepod group standing out as the largest contributors. The meroplankton, on the other hand, was mainly composed of larvae of organisms from Mollusca and Chordata.

In addition, we noticed that variations in community descriptors were more pronounced when assessing the temporal factor (interannual) and significant changes in some environmental parameters may have been responsible for these differences. However, we did not observe any substitutions between dominant species in the copepod assemblages, which were mostly composed of two dominant species (*Temora turbinata* and *Paracalanus* spp.). But it is important to highlight that the results about the structure of the zooplankton community in Praia do Futuro were a "punctual view" of two surveys (during the rainy season) in the region. Our results provide relevant information for future assessments of the impact on the zooplankton community where a desalination plant will operate.

4.1 Structure of the zooplankton community and dynamics of copepod assemblages.

Coastal ecosystems are important breeding grounds for various organisms that have pelagic larval stages such as fish, oysters and crabs (KOSLOW and WRIGHT, 2016; MACTAVISH et al., 2016; TROOST et al., 2009). Environmental changes can modify the dynamics of these larvae that make up the meroplankton, directly influencing species recruitment (MARCHETTI et al, 2024; MICHELSEN et al., 2017; CLOUGH et al., 1997). The highest significant densities ($p< 0.05$; ANOVA) of meroplankton occurred in conjunction with higher concentrations of chlorophyll-a, which may have benefited the development of these organisms (BRANDÃO et al., 2020; KIMURA et al., 2020).

Planktonic larvae play an important ecological role in marine environments, determining the dispersal potential of benthic organisms and serving as a trophic resource for many planktonic species (ERSHOVA et al., 2019; SHORT et al., 2013). In addition, they are useful tools in environmental management, even helping to define marine protected areas (JESSOPP and MCALLEN, 2007). Larvae of benthic invertebrates belonging to phylum Mollusca contributed the highest abundances of meroplankton during the study, and these organisms are quite frequent in the neritic pelagic zone (HIDALGO et al., 2014; WEIDBERG et al., 2013). It is worth noting that larvae of other organisms, such as lobsters, although not recorded in the sample, are species of economic interest that occur in the region (FREIRE et al., 2021); and nets with larger mesh sizes may be important for future monitoring of these groups in the region.

The higher densities of holoplankton and the phylum Arthropoda during the evaluation period was a characteristic similar to the mesozooplankton communities in other tropical marine environments (NEUMANN-LEITÃO et al., 2008; PELAYO-MARTÍNEZ et al., 2017; YANG et al., 2017; AMBRIZ-ARREOLA et al., 2018; FIGUEIREDO et al., 2018). Copepods were the most representative group throughout the study, which was expected as they dominate the mesozooplankton of various marine environments (ABEDI et al., 2023; LIM et al., 2020; PROTOPAPA et al., 2020; IZADI et al., 2018).

The species richness values were similar to those found on the continental shelf of northeastern Brazil (CAMPOS et al., 2017; COCEIÇÃO et al., 2021) and the diversity and equitability indices had average values, as reported for tropical marine environments (NEUMANN-LEITÃO et al., 2008). Overall, the richness, diversity and evenness values of the copepod assemblages increased in the ocean direction, as observed for the semi-arid continental shelf (CAMPOS et al., 2017). Species richness was the only descriptor that did not have significant spatial difference, however, temporal variations were significant for all the descriptors evaluated (richness, diversity, equitability and density). Changes in the circulation of water bodies, the availability of trophic resources and physical and chemical parameters are fundamental factors in altering the descriptors of the zooplankton community (FERNANDEZ de PUELLES et al., 2009; BRUGNANO et al, 2011; JOHNSON et al., 2011; ENGELAND et al., 2023).

The highest densities of copepods were observed in 2020, which may be related to a greater availability of food, indicated by higher concentrations of chlorophyll-a, as evidenced by principal component analysis (PCA) where the 2020 seasons were directly related to high chlorophyll-a values, suggesting an increase in photoautotrophic phytoplankton populations and, thus, available nutritive resources. The concentration of copepods was decreasing towards the ocean (outfall to catchment), a common pattern found for several tropical and subtropical marine regions (BONECKER et al., 2014; BECKER et al., 2018; SARMIENTO-LEZCANO, 2024; LAURA et al., 2021).

Overall, the composition of the copepod assemblages varied significantly ($p< 0.05$; ANOSIM) both spatially and temporally, highlighting the variability in the densities of *Paracalanus* spp. and *T. turbinata* (exotic species) as the main contributors to the dissimilarity between the sampling stations. These taxa were more representative throughout the assessment, with *T. turbinata* standing out as the dominant species at all sampling stations, and there was no substitution of dominant species during this study. The dissimilarity between the groups, even without changing the dominant species, may be related to the grouping of the high and low densities of these taxa into distinct groups.

The change in dominance in the zooplankton community is a phenomenon that depends on factors such as temperature fluctuations, changes in sea currents, degree of eutrophication, as well as variations in trophic resources that can select species with specific feeding habits (DIAS et al., 2023; TOMMASI et al., 2013; KEISTER et al., 2011; HOOFF & PETERSON, 2006). Some authors have highlighted water temperature as an important factor for oscillations in species dominance in oligotrophic marine regions (DAVIES et al., 2022; LANDRY et al., 2020; VON AMMON et al., 2020). Temperature was one of the parameters with lowest variations and no significance ($p<0.05$; ANOVA) during the study, suggesting fewer disturbances that impacted on the variation of dominant species in the region, which is considered oligotrophic (EKAU & KNOPPERS, 1999). Another possibility is that the time taken to evaluate the community was insufficient to detect such changes, since in order to better understand ecological dynamics long-term studies are necessary, as some observations require more time to obtain robust answers (O'DONNELL et al., 2023; SKJOLDAL et al., 2022; FULLGRABE et al., 2020; ARNDT et al., 1993).

It is important to note that the study area is close to an estuary, so it may suffer greater influence from the continental input during rainy periods, and also during periods of strong winds, where the river plume may be directed eastwards towards the assessed area.

4.2 Dominant species and environmental variables

Paracalanus spp. and *Temora turbinata* proved to be well adapted to the environmental conditions of the region, with high frequency in all samples and together representing approximately 84 % of the total abundance. Both are observed in oceans around the world and make up the order Calanoida, where the components are primarily herbivorous and omnivorous (MCKINNON & DUGGAN, 2001; JEREZ-GUERRERO et al., 2022; VENKATARAMANA et al., 2023; RUÍZ-PINEDA & SUÁREZ-MORALES, 2016; ZAKARIA et al., 2016). Both belong to two distinct families, with *Paracalanus* spp. making up the Paracalanidae, a family with a wide geographical distribution, being very common in tropical and subtropical regions, where they play an important role in marine trophodynamics (BOWMAN, 1971; TURNER, 1994).

In the present study, pH and dissolved oxygen values were inversely related to the abundance of *Paracalanus* spp. suggesting that positive variations in these parameters may have a negative impact on the development of the species. In addition, *Paracalanus* spp. had no correlation with chlorophyll-a, indicating that its diet may be related to heterotrophic organisms, as observed by Suzuki et al. (1999), in which they indicated that its main source of carbon was obtained through the ingestion of microprotozoa. The correlation between another species of the Paracalanidae Family (*P. carvus*) and chlorophyll-a was also unclear, with different responses between nearshore and offshore communities (SU et al., 2008). Low chlorophyll-a concentrations have been observed in ecosystems with a notable representation of *Paracalanus* spp. (ZHAO et al., 2022). Thus, it is possible that the concentration of chlorophyll-a does not regulate the development of *Paracalanus* spp.

The species *Temora turbinata* belongs to the Temoridae family, which includes coastal, estuarine and limnic marine forms (BOXSHALL and HALSEY, 2004). They are considered important controllers of phytoplankton densities, with diatoms as their main food source (JOHNSON and ALLEN, 2005). These taxa are frequently described in assessments of the mesozooplankton in regions of the continental shelf of northeastern Brazil (LAURA et al., 2021; CAMPOS et al., 2017; NEUMANN-LEITÃO et al., 2008).

T. turbinata, on the other hand, is considered an exotic species on the coast of Brazil (ARAUJO & MONTU, 1993) and has become an important contributor to mesozooplankton in marine and estuarine regions of the country (ANDRADE et al., 2022; BECKER et al., 2018; ARAÚJO et al., 2017; DIAS et al., 2009). This fact can be even more relevant when assessing the potential of an exotic species in the community itself, as predation and competition on native species can trigger adverse processes in the ecosystem (BARROETA et al., 2020; BOURDEAU et al., 2015). The co-genus *Temora stylifera*, previously quite abundant in coastal areas of Brazil (FERREIRA et al., 2009), seems to be losing ground to the invasive *T. turbinata* and moving to outer regions of the continental shelf of the semi-arid coast (CAMPOS et al., 2017). In this study, we observed average densities of *T. turbinata* that were 11 times higher than those of *T. stylifera*.

T. turbinata has a diversified diet (SANT'ANNA, 2013) and does not have an ovigerous sac, releasing its eggs into the water and thus enhancing dispersal to adjacent areas, which is an important characteristic for invasion, which does not happen with species that have an ovigerous sac, as the eggs retained in the sac become unviable if the females are predated or die due to other factors, such as unfavorable environmental changes (BARTH-JENSEN et al., 2020; KIØRBOE, 2006). It is a species well adapted to diverse conditions such as eutrophicated environments (DIAS et al., 2023) or environments with large variations in salinity (ARA, 2002), high turbidity (SOARES et al., 2018), and temperature fluctuations (CHEN et al., 2011). Nevertheless, it has proved to be extremely sensitive to oxygen depletion, suggesting this factor as one of the main controllers of the distribution of this species in coastal environments (HE et al., 2021). In the present study, *T. turbinata* was shown to be directly correlated with dissolved oxygen and temperature, as well as being strongly correlated with higher chlorophyll-a values, indicating its preference for consuming phytoplankton in its diet.

Negative impacts of desalination discharges on the phytoplankton community have already been mentioned (GOMES et al., 2023), which reinforces the importance of simultaneous monitoring of these groups during the operation of a desalination plant. The connection between phytoplankton and copepods is already known, so changes in this structure can lead to serious changes in ecosystem function (KÄMPF et al., 2023; RAHMAN et al., 2022; CHILMAWATI & SUMINTO et al., 2016; LI et al., 2013; URBAN-RICH et al., 2001), considering the fundamental importance of zooplankton at the base of the marine food web (MONTEMEZZANI et al., 2015; TREBILCO et al., 2020).

5. Conclusions

This study showed that the structure of the zooplankton community in the Praia do Futuro (NE, Brazil) was formed by holoplanktonic and meroplankton. The copepod assemblages had more pronounced temporal variations and that the species *Temora turbinata* and *Paracalanus* spp. proved to be well adapted to environmental conditions, dominating the mesozooplankton throughout the study.

The main parameters associated with the populations of *Paracalanus* spp. and *Temora turbinata* were pH, dissolved oxygen and chlorophyll-a concentration, the latter of which was highly correlated with the abundance of the exotic species *T. turbinata*, a fact not observed in *Paracalanus* spp. indicating that both species access different trophic resources in the ecosystem evaluated.

Given the trophic connectivity found between the primary producers and the dominant mesozooplankton, the relationship between the environmental variables and the taxa, as well as the importance of these organisms to the ecosystem, we suggest that there should be long-term monitoring (at least two times in each season) of these communities in order to detect and better understand the possible impacts of discharges from the desalination plant that will be installed in the region evaluated in this study. Finally, we hope that this work will be an important source for comparative assessments of this community, in order to measure possible changes resulting from the operation of the plant.

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CONCLUSIONS AND FINAL CONSIDERATIONS

Seawater desalination is an important alternative for minimizing the impacts of hydra scarcity. However, there is concern about the environmental impacts caused by this activity, mainly due to the effluents discharged into the ecosystem during the desalination process, which can have an impact on marine biota and especially on the most sensitive organisms, such as the planktonic community, a group of organisms that is very important in aquatic ecosystems.

We evaluated the results of published global studies in order to verify the impacts of discharges from different desalination technologies worldwide on coastal plankton. We found that phytoplankton were more sensitive to the environmental variations caused by the effluent from the plants and that the impacts caused by reverse osmosis plants were more damaging, both because of the high salinity and because the backwashing of the filters considerably increases the turbidity of the water, interfering with the photosynthetic process. We also found that few studies have addressed the influence of desalination discharges on zooplankton, and we suggest that research be carried out to better understand the behavior of these organisms under desalination activity.

In addition to the systematic review, we carried out a diagnosis of the structure and dynamics of the planktonic community in a region where a reverse osmosis desalination plant will be installed, located in Praia do Futuro (Fortaleza, Brazil). This type of study is of fundamental importance, as the lack of previous diagnostics (baseline assessment) prevents the comparative assessment of environmental impacts on plankton dynamics and structure.

We found a phytoplankton community composed mainly of diatoms and the highest densities were reported for the area of influence of the future desalination plant. Seasonality was an important factor for significant changes in the community and temperature proved to be an important parameter in explaining the variation in the community, as well as pH and conductivity. Some harmful species were among the fifteen most representative, especially the cyanobacterium *Trichodesmium erythraeum*, a species that forms large harmful blooms (HABs) and produces toxins that are harmful to human health.

The zooplankton had copepods as the main contributors to the total abundance of individuals, especially the species *Temora turbinata* and *Paracalanus* spp., which dominated the community throughout the assessment, proving to be well adapted to the environmental conditions of the region. *T. turbinata* (an exotic species) was positively correlated with higher chlorophyll-a values, a fact not observed for *Paracalanus* spp. suggesting that these species access different trophic resources. In addition, we noticed that variations in the descriptors of copepod assemblages were more pronounced when the temporal factor (interannual) was evaluated and significant changes in some environmental parameters may have been responsible for these modifications. It is worth noting that the assessment of the zooplankton community was only carried out during the rainy season (first semester), and the dry season (second semester) may bring changes with the arrival of the winds and the decrease in input from the estuary.

The strong temporal component indicates that the future monitoring actions should take this into consideration, as the effects of the desalination plan operation on the phytoplankton and zooplankton communities may vary depending on the time of the year. Also, the effects of the phytoplankton communities on the plant activities can variate throughout the year as evidenced by the community differences between rainy and dry seasons.

Given the sensitivity and importance of plankton to the marine ecosystem, we suggest that there should be long-term monitoring (at least two times in each season) of these communities in order to detect and better understand the possible impacts of discharges from the desalination plant that will be installed in the region evaluated in this study. Finally, we hope that this novel research will be an important source for comparative assessments of this community, in order to measure possible changes resulting from the operation of the plant.