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Economic–Financial Assessment of Seawater Desalination Plants in Northern Chile to Reduce Hydric Scarcity and a Proposal for the Environmental and Sustainable Use of Brine Waste by Cultivating the Microalga *Dunaliella salina* to Produce β-Carotene

Tomas Gabriel Bas *, Rodrigo Fariña, Fernanda Gallardo and Macarena Vilches

Escuela de Ciencias Empresariales, Universidad Católica del Norte, Coquimbo 1780000, Chile; rfarina.llanos@gmail.com (R.F.); fernanda.gallardo@alumnos.ucn.cl (F.G.); macarena.vilches@alumnos.ucn.cl (M.V.)
* Correspondence: tomas.bas@ucn.cl

Abstract: Climate change and global warming generate serious consequences and disturbances by drastically modifying historical temperature and precipitation patterns. Water scarcity is one of the most revealing phenomena of these instabilities. This transdisciplinary bibliometric and economic–financial research focuses on analyzing two aspects: first, the feasibility of implementing seawater desalination plants as a solution to water scarcity in northern Chile. Investment and amortization costs of the desalination plants were determined (NPV-IRR-IRP). NPV showed a positive value indicating a recovery of the initial investment and a surplus over profitability. The IRR was higher than the discount rate calculated for NPV, which showed that the investment project was accepted. The IRP indicated that the initial investment of the plant would be recovered in 3.7 years. Second, an innovative and environmentally sustainable solution to the brine (NaCl) waste generated by desalination plants is proposed through the cultivation of *Dunaliella salina* microalgae tolerant to high brine concentrations to produce β-carotene. The analyzed desalination plants and the sustainable use of brine residues offer interesting economic perspectives to a 10-year projection establishing a surplus over profitability. The SWOT analysis estimates an excellent production of β-carotene through the microalgae and alternatives to the problem of sea pollution by concentrated brine waste.

Keywords: hydric scarcity; desalination plant; freshwater; brine; north of Chile; business model; *Dunaliella salina*; β-carotene; waste

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1. Introduction

Climate change and global warming are phenomena that are advancing indiscriminately, affecting all corners of the planet in different ways [1,2]. Given the uncertainty that this generates, numerous parallel sustainability agendas and initiatives have emerged that address the problem from different angles [3,4]. It has been possible to diagnose and determine some variables such as alterations in ocean temperatures, changes in terrestrial ecosystems, intense floods and/or droughts, a decrease in the thickness of snow and ice layers in the polar ice caps, the shortening of cold seasons, the melting of glaciers, a decrease in the extent of permafrost, and a sea level rise that provide clear evidence that global temperatures are increasing [5]. However, in some regions, such as Chile, this manifestation is expressed in a more heterogeneous way due to the enormous extension of its territory, which from north to south reaches 4270 km. This makes it possible to identify the study problem that is linked to the water scarcity that mainly affects the north of Chile. This refers to the lack of volume of freshwater for its supply and use, calculated as a negative relationship between the consumption of freshwater for people and the available supply of this good in a given area [6]. In Chile, the use of freshwater is legislated and guaranteed by the National Constitution enacted in 1980, where the rights to this vital element have the status of "property rights" [7]. According to this author, a self-proclaimed "Water Code" was created. The Code defined this resource as an economic good that can be acquired transactionally through the payment of a fee. This generates a business of the vital element, where of the 79% of the total volume of freshwater available for human consumption, only 1% is freely shared by consumers.

Based on this scenario, options are analyzed to provide an alternative source of fresh water to generate short- and medium-term solutions to water stress through seawater desalination plants using an RO system. This research focuses on the north of Chile (specifically, the region of Coquimbo, located in a maritime coastal area on the Pacific Ocean) because it is one of the areas of the country most affected by drought and the scarce availability of drinking water, but at the same time, it is a geographical point of reference for agricultural production in the north of Chile [8–10]. The research has two main objectives, which together constitute a differentiating novelty. The first objective is to determine the economic and financial viability by calculating the investment and amortization costs of desalination plants in the region of Coquimbo (Chile). An analysis of the net present value (NPV), internal rate return (IRR), and interest rate parity (IRP) for investment and depreciation costs was performed. The second objective is to use the surplus of brine generated after desalinating seawater, which usually is returned to the sea in the same place where it was extracted, generating an oversaturation of salt and high toxicity in the entire ecosystem. To avoid this, the use of the halophilic microalga *Dunaliella salina* is proposed as a new business model related to the production of β-carotene, simultaneously reducing the available brine in the sea water [11].

In the following subsections, we will address each of the elements that are related to this research, specifically to hydric scarcity, the regulation of water in Chile, seawater desalination, desalination plants in Chile, desalination waste, and, finally, the microalga *Dunaliella salina* for β-carotene production.

1.1. Hydric Scarcity

The combined effects of global population growth, industrialization, agriculture, and urbanization are driving unprecedented demand for freshwater in human history [12,13]. This is compounded by climate change, which is a global phenomenon directly affecting the quality and availability of freshwater [14,15]. However, there are no figures that allow us to hazard an accurate estimate of the scale of the freshwater scarcity crisis and the magnitude of the socio-economic problem behind it, as there are different direct and indirect variables that together play a crucial role in the balance between water supply and demand [16]. Currently, just under half of the world's population, approximately 47%, lives in water-scarce areas, while it is estimated that, in 2050, 57% of the population will live in areas that experience water scarcity at least one month per year [17]. This author estimates that the global demand for water for all uses will be about 4600 km^3 per year, with the global demand for freshwater for agriculture being one of the fastest growing, potentially increasing by 60% by 2025.

1.2. Water and Regulation in Chile

Chile does not have an integrated freshwater basin management system, which limits the sustainable management of this vital resource in areas of scarcity or extreme scarcity. Furthermore, it does not consider the interdependence between freshwater and different ecosystems [6]. The demand for freshwater by mining companies in Chile to operate at full capacity has caused friction and uncertainty between mining companies and society. However, it is not the mining sector that uses the most water in Chile but the agricultural sector, with approximately 72% of the total freshwater available for use [7]. The emergency plan delivered by the Regional Government of Coquimbo [18] shows that Chile faces a dramatic and poorly controlled problem, where legislation is needed toward the development of public policies that protect sustainable access to water as well as favor new sources of freshwater supply.

From this perspective, it is important to mention that the desalination process constitutes a differentiated legal fact in which diverse effects are produced in the extraction of seawater, in the process itself, and in the use or destination given to the desalinated water and its residues (mainly brine), involving diverse legal figures throughout the process [19]. In Chile, the regulation of water is the responsibility of the Civil Code and the 1981 Water Code [20]. The latter allowed for the privatization of this vital element, generating several conflicts between water as a human right and water as a tradable good in the market. This shows that, in Chile, the issue of water, its use, and ownership is still unresolved, and desalinated water could be another potential source of conflict [21].

The rural area of the Coquimbo region (Chile) is composed of 142,470 inhabitants distributed in 2490 localities, where 66% have access to drinking water from the public network and 13% have access from wells, while 16% do so through tanker trucks [18]. Analyzing these data and the problem of the existence of water scarcity and the lack of public/private support for the different rural sectors, this study is based on the need to contribute to understanding the problem and facilitate support related to access to fresh water through alternatives other than those currently considered (snow, fog, and rainwater harvesting, as well as groundwater).

1.3. Seawater Desalination

Some authors estimate that there are about 16,000 operational desalination plants in the world producing up to 95 million m^3/day of desalinated water for human use (almost half in the Middle East and North Africa region) [22]. As a result, global desalination capacity in 1980 increased from about 5 million m^3/year to about 90 million m^3/year in 2016, and this trend continues with new technologies [12]. However, some studies estimate that Reverse Osmosis (RO) desalination plants, which currently account for 69% of global production, consume between 4.0 and 4.5 kWh of electrical energy and emit between 0.08 and 4.3 kg of CO_2 in the process [21,22].

There are several technologies developed to desalinate seawater, and although they have different characteristics depending on the type of energy required and the design, they all have the same objective: to reduce the concentration of dissolved salts in the extracted seawater as much as possible. This makes it possible to distinguish between processes that separate the water from the salts and those that actually separate the salts from the solution [23–25]. Modern desalination, industrially speaking, has existed since the 1960s and refers to processes aimed at removing excess salt, iodine, and other minerals present in seawater and brackish water with the objective of obtaining fresh water suitable for use and consumption [26]. This alternative is often considered a cost-effective, environmentally safe, sustainable, and drought-proof source of water [24,27,28]. However, more innovative desalination technologies are always being researched and invested in to improve the economics and efficiency of the process in order to reduce the cost of freshwater and its waste [26]. The thermal type desalination system, which uses solar heat to evaporate and distill seawater, is gaining popularity [29,30]. This system is beginning to be recognized as efficient, sustainable, and economical, although it depends on effective temperatures and available sunshine hours. On the other hand, there are membrane-type desalination plants that use electrical power to pump seawater through membranes, although this involves a cost in electricity and is not always available in all regions. In the past, the cost of seawater desalination was less than USD 0.50 /m^3; however, due to the rising cost of materials, desalination values have been increasing in some regions of the world to a cost of USD 1–1.5 /m^3 [31].

For more than 60 years, there has been a propensity to build large-capacity desalination plants in terms of infrastructure, which has contributed significantly to an increased flow of freshwater supply to large coastal cities in different parts of the world [32]. Mega seawater desalination projects, both regional and national, are being planned in countries such as Spain, Australia, Israel, Algeria, and Singapore, which have large freshwater deficits, with the aim of meeting 20–50% of long-term freshwater needs [32]. As a complement, the case of Australia is mentioned due to the availability of its comprehensive site-specific data and the suitability of its geography, geology, climate, and urban form for the use of the desalination technologies under consideration. Since about 1975, south-western Australia has experienced a significant reduction in rainfall, which, combined with population growth, has led to an increased reliance on desalination to secure water supply. The Perth region is currently the largest user of seawater desalination among Australian cities. Half of the water supply in and around Perth comes from two large seawater reverse osmosis (SWRO) plants; the South Sea Water Desalination Plant and the Perth Seawater Desalination Plant supply 320,000 m^3/day and 145,000 m^3/day, respectively [32]. Another example of a large-scale, energy-efficient RO desalination plant is the "Tuaspring" plant in Singapore. It is equipped with a self-sufficient on-site power plant, which allows for significant operating and capital cost advantages by using only one intake and one outfall and associated pumps for both plants [33]. Similar implementations could be considered for Chile; however, it should not be forgotten that it is a developing country, and the associated costs are often prohibitive [34].

1.4. Desalination Plants in Chile

Chile is a pioneer in water desalination with the development of the "Las Salinas" project in 1872. Today, the desalination process is mainly used by mining companies as well as for supplying populations in areas of great drought and isolation in the north of the country, such as the city of Antofagasta and surrounding areas, Arica and Coquimbo [35–37]. In fact, mining companies are being encouraged to use exclusively desalinated water for their operations [38]. In Chile, the relevance of seawater desalination to support freshwater supply has been increasing in recent decades due to the steady increase in freshwater demand from mining, rural, and urban sectors. This is also due to the significant reduction in the cost of desalination, mainly due to technological innovation and advances, especially in the RO process [39]. In Chile, desalination projects are not incorporated as a category in the Environmental Assessment Service (SEA), which would allow for establishing the impact that these projects would generate in the environment where they are established, but they are presented as environmental remediation (environmental sanitation) and/or pipeline construction, so there is no relevant environmental study [28,34,38]. At the end of 2019, Chile had 24 desalination plants in operation and 22 projects in various stages of progress. According to the records of the Environmental Impact Assessment Service of the Ministry of the Environment, between 1999 and 2017, 13 projects related to water desalination were submitted, of which 9 would be destined for the productive sanitation sector. At present, and with projects not yet validated or executed by the Chilean government, according to the "Asociación Chilena de Desalinización" (ACADES), there are around 46 desalination plants throughout the country, with the highest concentration in the regions of Antofagasta, Atacama, and Coquimbo. It is important to note, as mentioned at the beginning, that much of this funding is provided by mining companies, which have a close relationship between their smelters and the desalinated water used in them [40].

1.5. Desalination Waste

Unfortunately, even with current technologies, approximately 50% of the total seawater pumped to desalination plants is returned to the sea as brine, making it extremely concentrated and associated with negative environmental impacts [38,41]. This concentration causes significant changes in water temperature, chemical oxygen demand, suspended solids, and concentrations of heavy metals of interest such as chromium, copper, zinc, arsenic, cadmium, mercury, lead, nickel, iodine, and other minerals and metals. Although they are of natural origin, their agglutination in a restricted space makes them highly polluting for the biota [38,42,43]. In marine systems, salinity naturally varies between

33 and 39 practical salinity units (PSU), where the different species that inhabit there are adapted and, in many cases, specialized to these specific salinity and temperature conditions [44]. The brine generated as waste during the desalination process could be calculated as 1.5 units of brine for each unit of desalinated water, which is equivalent to 141.5 million m^3/day in a desalination plant in Saudi Arabia, United Arab Emirates, Kuwait, or Qatar [22]. According to the same authors, these countries represent 55% of the world's total desalinated water.

However, potential solutions are evident, as there are systems in the conceptual stage that use desalination wastewater for CO_2 capture and desulphurization instead of commonly used limestone which is not readily available. Therefore, the proposed novel process is a suitable solution to address the problem of environmental pollution from brine discharged into the sea and SOx absorber feedstock restrictions by using only desalination wastewater that is generally discharged and therefore readily available [45]. This opens up different and new business models that are more sustainable and where, in the manner of a circular economy, everything is used and is what is known as a "winner–winner", i.e., freshwater is obtained, and much of the waste is used in CO_2 desulphurization processes, without the need for limestone.

1.6. Microalga Dunaliella salina and β-Carotene Production

The *Dunaliella* genus is a green hypersaline microalga that is unicellular and biflagellate with an ovoid shape from −5 to 5 µm. It differs from other green microalgae by the absence of a rigid polysaccharide cell wall and the presence of an external cell membrane composed of glycoproteins [46–48]. *Dunaliella salina* have been identified for treating brine waste generated by desalination plants and as a potential source of high-value products such as β-carotene, fatty acids, and antioxidants. The process of treating brine waste with the microalgae is a two-stage approach. In the first stage, the brine is treated with *Dunaliella salina* to extract desired components (i.e., β-carotene). This can be carried out using either a static or dynamic system. In the second stage, the extracted components are then used in the creation of value-added products in different industries such as food, pharma, and petroleum. The development of a business model for treating brine waste requires the consideration of several factors. First, the extraction process cost must be considered. Additionally, the cost of producing the desired value-added products must also be pondered. Finally, the potential market demand for these products must be evaluated [49,50].

The large-scale cultivation of this variety has the advantages of having a high development rate, growing under salt stress, having limited nitrogen, and having a low cost of production, but its ecology is not fully understood, even today [46,51]. Commercial mass *Dunaliella salina* production is carried out in open tanks. Four open-culture systems are commonly used: large shallow ponds, tanks, and circular ponds and raceway ponds. Likewise, photobioreactors are being designed to make the culture and purity of microalgae more efficient for high-quality applications such as food, cosmetics, healthcare, and pharmaceutical compounds [47]. Nevertheless, *Dunaliella salina* cells accumulate different protein compounds, fatty acids, and fine chemicals such as xanthophylls (zeaxanthin, lutein, α- and β-cryptoxanthin, violaxanthin, and echinenone) and the family of carotenes. (α-carotene, all-trans β-carotene, 9-cis β-carotene, 15-cis β-carotene, and lycopene) [46]. *Dunaliella salina* is also very successful in biological wastewater treatment and in the removal of groups of toxic contaminants. They allow for heavy metal separation, for example, reducing environmental damage [52].

Dunaliella dried biomass comprises 50–80% protein. More notably, the vital amino acid (EAA) composition of *Dunaliella*, as indicated with the aid of the Essential Amino Acid Index (EAAI), can attain superior protein quality for human requirements following reference levels set by the Food and Agriculture Organization of the United Nations (FAO) [53]. *Dunaliella salina* not only attract attention for the production of lipids and β-carotenes and as biofuel, but since the COVID-19 pandemic, they have also been investigated with increasing interest as a protein expression model. As this microalgae has unicellular photosynthetic characteristics, it has specific biological and growth properties that can be applied to the development of vaccines [54]. Additionally, the β-carotenoid is the most significant algae in aquaculture and biodiesel fuel production.

Since the 1980s, there have been 46 large-scale *Dunaliella salina* cultivation factories in operation, producing more than 1000 kg of microalgae per month, mostly in Asian countries [55]. This microalgae cultivation became one of the major manufacturers for β-carotenoid metabolites. The microalgal biomass manufacturing marketplace has reached approximately 5000 hundreds of dry matter/twelve months and has a turnover of ~USD 1.25 × 109 USD per year [56]. Culture systems include two styles: open-culture systems (pools) and closed-culture systems (photobioreactors).

The cost of harvesting microalgae is significant, accounting for 20–30% of total production costs, due to the high energy requirements resulting from the low biomass concentration, small size, and similar density to water. Centrifugation is the most common and efficient technology for harvesting microalgae, but it requires a high capital investment and energy costs. Spiral plate technology (SPT) centrifuges can reduce the energy consumption of centrifugation, consuming, on average, 2.5 kW h/m^3. Membrane technologies can also be used for microalgae harvesting, especially for microalgae with low biomass concentrations, such as Dunaliella salina. Membrane filtration can reduce the energy required for centrifugation and enable the recovery of valuable compounds. Integrating membrane pre-harvesting and centrifugation can reduce the overall energy consumption and investment costs. The energy consumption of integrated membrane-centrifugation systems is estimated at 0.169 kW h/kg of dry algae weight, compared to 0.5 kW h/kg for traditional centrifugation. The increase in the microalgae concentration achieved by harvesting with membranes has no impact on SPT power consumption. [57].

This research analyzes the feasibility of implementing a seawater desalination plant in the Coquimbo region. It selects the relevant type of the process and the use of its waste based on the bio-circular economy with an economic feasibility study. To this end, the most appropriate and relevant type of desalination process for the region conditions will be selected, outlining the stages. Investments, costs, and depreciation for the plant implementation will be determined. This will enable us to finally elaborate some business model proposals for the use of freshwater desalination waste (brine).

At least two research-related questions are posed.

1. Could the installation of seawater desalination plants combat the water scarcity that afflicts the Coquimbo region in Chile?
2. Is it possible to generate new profitable business models through the integral use of the waste generated by the microalgae *Dunaliella salina*?

To answer these questions, the research is structured by a bibliographical discussion, setting out the aforementioned objectives. It describes a hybrid review method of research and concludes with the results, a discussion, and the conclusions.

2. Materials and Methods

The methodology used is a mixed-data triangulation type (qualitative and quantitative) [58–62] based on a bibliometric documentary category of research. This is a research approach used when, for different reasons, it is not possible to have access to primary sources, either due to the cost or time. Consequently, the research is based on secondary data already validated by the international scientific community to have an overview from documentary bibliometric information and case studies to achieve the results and facilitate their understanding and interpretation. The documentary method is part of the sociology of knowledge and is a theoretical–methodological instrument that seeks to overcome the opposition between objectivity and subjectivity on the basis of already-validated documents [63,64]. Like other analytical methods in qualitative research, the analysis of documents from different scientific databases requires them to be thoroughly examined and interpreted as input for the construction of a new database. This is accomplished using transparent and rigorous approaches used in primary research that serve to integrate the findings of different studies that answer a research question [59]. This is based on the acquisition, cross-referencing, and triangulation of data to generate unprecedented significance in a different context to develop new empirical knowledge [58]. On the other hand, the quantitative component, although also based on secondary data, was the basis for estimating the investment and depreciation costs of seawater desalination plants and proposing economic projections through NPV, IRR, and IRP for the use of brine waste. It is important to point out that the research, even if it uses secondary literature in its development and analysis, is not considered a review because it provides unpublished data from the economic and financial analysis.

Ultimately, data exploration involved a selection, compilation, and review of scientific literature (already presented in the previous sections) through the reading and critique of the theoretical and bibliographical instruments found according to Boolean operators. These seek to interpret an experience related to predetermined keywords from different sources of information and are characterized by an interpretative approach to the findings and gaps in the research itself [65,66]. To make the search effective, documentary sources or bibliographic databases were chosen by discipline or topic from: Science Direct, Agricola, Compendex, Derwent, Statistics Canada, Scopus, Web of Science, Innovation Index, and GeoIndex. These were combined to counteract the degree of data overlap that may exist between them.

The search was carried out on the basis of the selection profile by relations between descriptors using logical or Boolean operators (AND, OR). The bibliographic search was structured considering the degree of sensitivity (recovery rate) and specificity (precision rate) based on the definition of the construction of the research questions and objectives to delimit the search for information [66]. A selection and ordering of the sources used was carried out through the identification of keywords such as: drought, water scarcity; mining; agriculture; climate change; sustainability; desalination plants, types of desalination plants; freshwater; waste; NaCl; algae. Figure 1 shows a flowchart of the interactions of the keywords used in the research. Complementary words of the same root as the mother words were added to help understand and explain the dynamics related to seawater desalination and the theoretical tools and alternatives of analysis with the proposed environmental sustainability through the new business model and the commercial use of the waste NaCl.

In order to answer the two research questions and to be able to resolve the stated objectives, the methodology privileged was to collect validated information from the most relevant sources, perform an exhaustive review, and collate the scientific information saved, which would then allow us to interpret the retained inputs and thus have, through triangulation, strong results to reach a conclusion and contributions that would serve as a basis for reflection for future research [67].

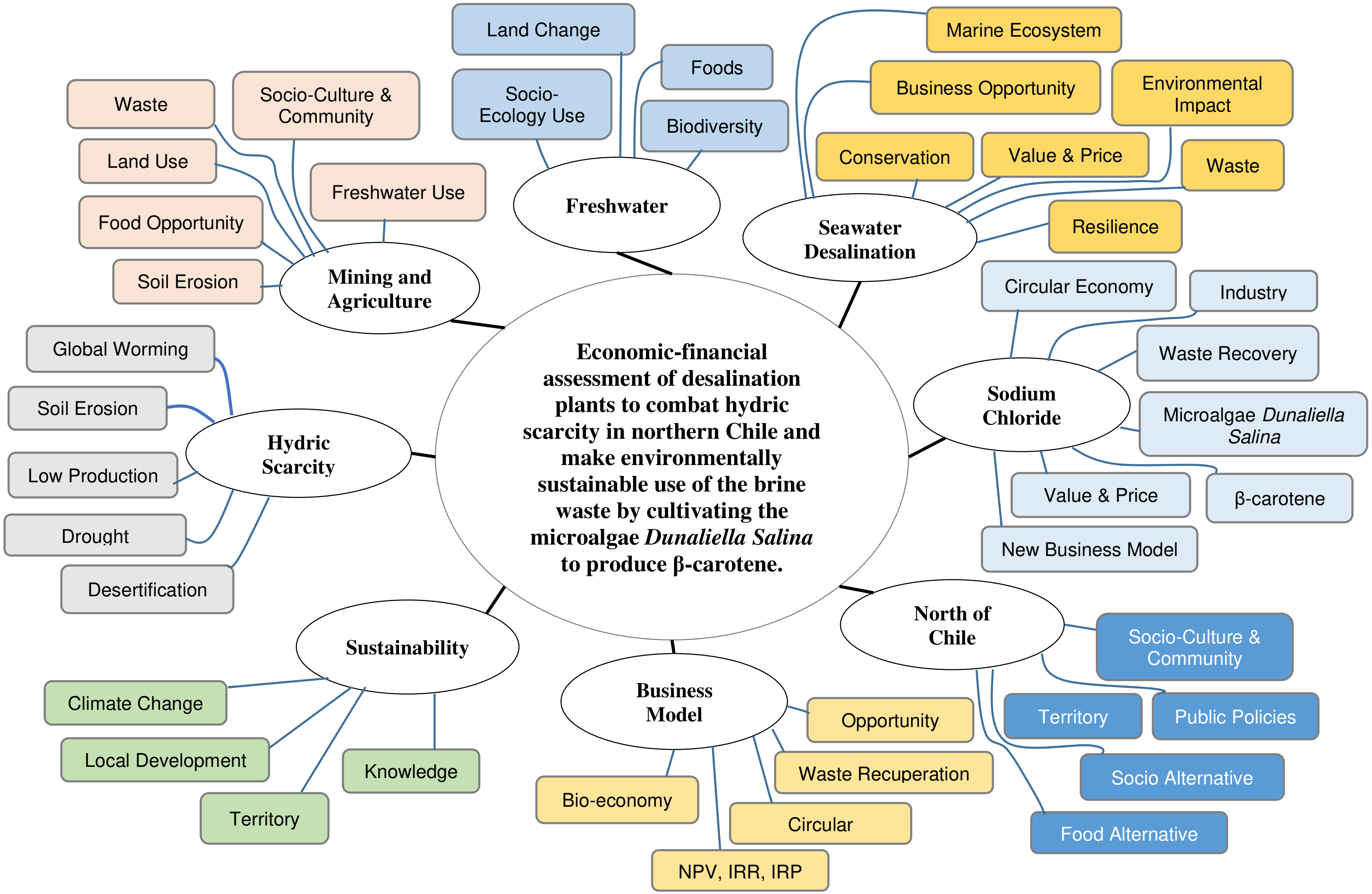

Figure 1. Flow chart of the interactions of the parent keywords used for the research.

The information needed for the literature search strategy is expressed in one word or a short phrase (e.g., seawater desalination). Some concepts were split into half to have more of a research scope, e.g., "seawater desalination" in "seawater" and "desalination". All words or expressions within a concept are synonyms or quasi-synonyms, and, where necessary, related words have been cross-referenced. We used Boolean operators and parentheses, e.g., (word1 * OR word2 * OR . . .) AND (word7 * OR . . .). In addition, exact expressions ("xx") and appropriate field codes were used (e.g., in Compendex-> WN KY). The "{English} WN LA" was used too, but literature in Spanish was accepted as well, which finally yielded more than 2800 identifiable results. Subsequently, to optimize the search strategy, different options were tested, eliminating some keywords that were too generic or not directly related to the search. It was found that the number of results was too high; therefore, in order to narrow down the search more specifically, we used the abstracts and titles that matched the object of research and the title of our research. Based on the analysis of the results obtained (reading the titles and detailed references, if necessary), we were able to analyze and classify the different articles considering those that came closest to our research question, and then we dynamically modified the selection strategy until we reached 120 results that were considered sufficient to classify and consult. The time window selected was from 2013 to 2023, mainly because of the need to have updated data related to the object of the search. In addition, a time window before 2013 was opened to include articles that could be classics in the subject analyzed or made great timeless contributions, even exceptionally from previous years, if necessary.

Once the information collected had been established and characterized, we proceeded to the analysis of the references collected according to the established objectives [67] and based on the keywords (roots) and those directly related to the former; the specific search was carried out for each objective, as shown in Figure 1. The following shows the three selected objectives and how they were methodologically approached.

1. Select the type of desalination process and the stages involved. Qualitative: survey of sources; review; collation; interpretation. Keywords: Desalination, desalination processes, stage of desalination RO.
2. Determine the investments, costs, and depreciation for the implementation of a seawater desalination plant in the region of Coquimbo, Chile. Quantitative: through deductive and sequential methods, where the results are expressed numerically from figures, statistics, percentages, etc. that will serve as inputs in the analysis of the results. Keywords: Initial investment of a desalination plant; fixed and variable costs of a desalination plant; expenses of a desalination plant; depreciation of a desalination plant.
3. Develop proposals for the use of waste from the freshwater desalination process based on the circular economy. Qualitative: survey of sources; review; collation; interpretation. Keywords: Reuse of seawater for RO, circular bioeconomy, *Dunaliella salina* microalgae, natural β-carotene, marine ecosystem.

Once the respective search had been carried out and analyzed, the results were filtered according to the pre-established criteria and validated by the selected databases: Science Direct, Agricola, Compendex, Derwent, Statistics Canada, Scopus, Web of Science, Innovation Index, and GeoIndex.

The text describes the methodology used in a study that relies on secondary data due to cost or time constraints. The approach used is a mixed-data triangulation type that combines qualitative and quantitative methods. While the documentary method used in this study seeks to overcome the opposition between objectivity and subjectivity by relying on already-validated documents, there is an alternative methodology called content analysis that also involves analyzing existing data, and it can have similar characteristics.

As a complement, there are different methodologies similar to the one used in this research. The closest is "content analysis". This methodology also involves analyzing text, images, or other types of data to identify patterns, themes, and other meaningful information [68]. Like the documentary method, a content analysis can be used to gain insights into a research question without conducting primary research. It also involves a rigorous approach to data analysis and can incorporate both qualitative and quantitative methods. Additionally, content analysis can use pre-existing datasets from multiple sources to generate unprecedented significance in a different context.

Overall, content analysis is a viable alternative methodology that has characteristics similar to those of the documentary method and can be used in studies that rely on secondary data. It could be considered as an alternative approach for future studies, if appropriate.

3. Results and Discussion

3.1. Type of Desalination Process

Different industrial desalination processes were identified, the most common being those that separate seawater into two main streams: one containing a low concentration of dissolved salts and the other consisting of a highly concentrated brine (process waste) that is finally returned to the primary sources of extraction, usually the ocean, with the negative impact this has on the surrounding ecosystem at the trophic level [69,70].

Seawater desalination methods are divided for practical purposes into two broad categories. One is thermal evaporation, while the other is membrane-based separation. In thermal processes, heat is used to evaporate the water from the salt solution, and then that water vapor is condensed and recovered as freshwater. The most common thermal desalination processes are [71]:

1. Multi-stage flash distillation (MSF).
2. Multi-effect distillation (MED).
3. Vapor compression (VC).

On the other hand, membrane-based separation uses a mechanical pressure, an electrical potential (can be a sustainable or commercial power line or hybrid sources), or a concentration gradient as the driving forces across a semi-permeable membrane barrier that allows for separating salt on one side and the resulting freshwater on the other. They differ from each other by the type of membrane each has. The best-known individual membrane processes are [24]:

4. RO: consists of a membrane that prevents the passage of bacteria, protozoa, algae, viruses, dissolved organic matter, and divalent and monovalent ions, and its structure has no pores.
5. Flash Evaporation (NF): has a pore size of approximately 0.001 µm and, unlike RO membranes, does not retain monovalent species such as sodium and chlorine.

Other processes, less used by industries, include:

- Ultra-Filtration (UF), with a pore size of 0.01 µm.
- Microfiltration (MF), with a pore size of 0.1 µm.

The latter two, in contrast to the above-mentioned membranes (OI–NF), only allow for the removal of bacteria and suspended solids.

- Membrane desalination (MD).
- Electrodialysis (ED).

Commercially, the most competitive technologies used worldwide are based on the RO, MSF, and MED processes. Of these, RO is leading by 80%, followed by Flash Evaporation, also called Multi-Flow Distillation (NF–MSF) [72,73].

Tables 1 and 2 show different existing desalination processes, with indicators such as energy consumption, unit costs for each, the global trends they have, and the energy sources they work with [74,75].

Table 1. Typical energy requirements for different desalination processes [75].

Process	Thermal Energy (kWh/m^3)	Electrical Energy (kWh/m^3)	Comments
MFS	12	3.5	Feed steam >110 °C
MED	6	1.5	Can operate <70 °C
RO	-	4–7	-

Note: MFS—Multi-Stage Flash Distillation; MED—Multi-Effect Distillation.

Table 2. Processes and relevant indicators of costs, consumption, and energy sources [74].

Relevant Indicators		Indicators			
		Energy Consumption	Unit Costs	World Trends	Power Source
Process	RO	From 2 to 2.8 kWh/m^3	USD 0.6/m^3	Growth	Electric
	Electrodialysis	From 16 to 19 kWh/m^3	USD 58/m^3	Static	Electric
	Multi-Effect Distillation (MED)	From 3.4 to 4 kWh/m^3	USD 1.5/m^3	Decreasing	Heating Electric
	Multi-Stage Flash Evaporation (MSF)	From 5 to 8 kWh/m^3	USD 1.10/m^3	Decreasing	Heating Electric
	Solar Distillation	-	USD 28/m^3	Static/Rising	Solar Energy

The different processes, with a membrane, achieve the rejection of substances dissolved in the water, such as mineral salts, where membranes with special characteristics are permeable to water but not to the compounds present in it, which are rejected and removed from the process [24,73,75].

Based on the above, the RO process would be the most suitable method to be installed in northern Chile. As already observed, RO is a process that works by applying pressure on a saltwater solution and passing it through a semi-permeable membrane whose function is to pass the saltwater and divide it in two—on the one hand, the water without salts, and on the other, the water with a very high concentration of NaCl. It is worth mentioning that this water treatment process is carried out thanks to the contribution of external energy in the form of pressure, which overcomes the natural osmotic pressure present in the solution. In addition, the salinity of seawater contains contaminants such as pathogenic microorganisms, heavy metals, and various other organic and inorganic substances that can negatively affect water quality, so it must be treated to combat these pathogens and pollutants. On the other hand, it is important to note that the RO process offers the finest filtration currently available, rejecting most dissolved and suspended solids while preventing the passage of bacteria and viruses, resulting in pure and sterile water. Meanwhile, impurities remaining on the membranes are subsequently washed away by the same water stream [36,38,76]. In this way, the system performs a constant self-cleaning. Through this technique, it is possible to treat from 95 L per hour to more than 1,704,000 L per day [77]. On the other hand, an RO unit called "Hero" provides highly purified rinse water before it enters the RO system, which increases the recovery rate of the system from 60% to 95%, saving 34 million gallons per year [78].

In summary, some advantages of the RO process are [79]:

- It is a very effective method: In the generation of freshwater suitable for human consumption, the RO method has proven to be effective and the most widespread in the world. Desalination plants, when properly designed, are capable of producing very-good-quality water.
- The power source is the ocean: Seawater can serve as a source of unlimited resources, even assuming that all water consumed on land comes from desalination. This would allow, even in times of drought, the world's population to have access to water for drinking and agriculture.

- It can eliminate water crises: Drought crises occur in many parts of the world, and since this water is readily available in virtually unlimited quantities, the technology could be used to alleviate these crises.
- Can preserve existing resources: Emphasis should be placed on preserving as many of the planet's available freshwater resources as possible, as these are limited. In this way, these resources could be reserved for shortages. At the same time, with good waste management, the sea from which saltwater is extracted can be preserved.
- Plants are built in suitable locations: Desalination plants are built far away from residential areas, and they are located on industrial sites so as not to expose the population to any risk. In addition, a single plant can produce more than 500 million liters of water suitable for human consumption.

However, it is important to note that, for the production and use of desalinated seawater, a relevant factor for the process must be considered: the electrical energy. According to studies conducted in 2017 by the Chilean Copper Commission [80], in 2016, electricity represented 9% of the operating costs of large copper mining companies in Chile, considering that these entities were the first to implement desalination plants in the country.

Regarding the seawater desalination process, there is a close relationship between seawater use and energy consumption, to such an extent that the cost of water is inescapably transformed into energy costs [75]. This is reflected in the experience of Grupo CAP (Compañía de Acero del Pacífico) [81], where the energy required for the desalination process was 67% of the cost, while for pumping water, which is extremely energy-intensive, it represented 97% of the total operational cost of transport [82].

Figure 2 shows how the operational costs of a plant using the RO process to desalinate seawater are distributed. In this respect, it can be seen that the cost of energy represents 44% of the total operating cost, which, in some way, is a variable of high impact, as it is a value that affects the final cost of the water obtained, so in the case of the Coquimbo region, it is a variable that must be considered when generating a project of this magnitude. However, there is an open discussion, where, for some authors, we are in the presence of very high electricity costs, and for others, we are in the presence of rather moderate costs, so it is important to consider sustainable energy systems such as solar panels or wind energy and even hybrid systems depending on the availability in each sector.

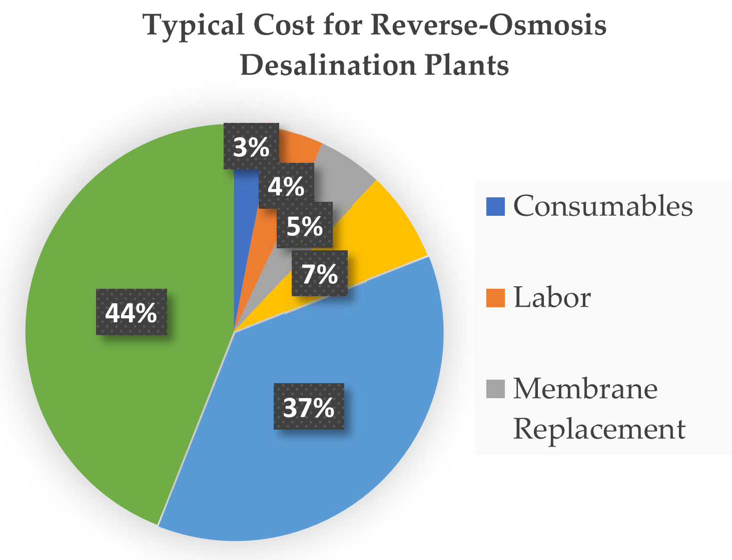

Figure 2. Distribution of the main operational costs of an RO plant [83].

The absolute minimum energy required to obtain one cubic meter of freshwater from a mass of seawater at 20 °C, calculated according to the second law of thermodynamics, is 0.79 kWh/m^3, regardless of the separation technique used. For most brackish waters, the minimum energy requirement is much lower. For a process with a recovery rate of 50%, with an initial solution of 3.5% NaCl, the minimum energy increases to about 1.1 kWh/m^3. In addition, the common energy consumption of the SWRO desalination plant is of the order of 3.5 kWh/m^3. The range of energy demand for the RO process itself, depending on the salinity of the feed water, the recovery rate, the efficiency of the pumps, and the efficiency of the energy recovery system, is between 1.7 and 2.5 kWh/m^3. Additional costs, such as pumping, pre-treatment, brine discharge, and electrical energy used within the plant, total between 0.3 and 1.5 kWh/m^3. Therefore, the total energy consumption is 2.0 to 4.0 kWh/m^3. Smaller facilities, remote locations, and a lack of experience in design and/or operation can increase energy consumption in the range of 3 to 7 kWh/m^3 [24].

Stages of RO

This process, like all the others, has different stages, which consist in the first instance of a specific mesh filter that is made up of a metallic structure inside which there is a concentric cylinder covered with a plastic, polymeric, or stainless-steel mesh. The filtering process occurs because the size of the holes in the mesh allows for the passage of materials of a dimension smaller than their diameter (this is due to the fact that the RO in its structure does not have pores), thus separating foreign particles. These filters are characterized by the density of their holes, which are one linear inch. The more holes there are, the higher the mesh number and the smaller the particle size it allows to pass through. The placement of denser meshes leads to frequent blockages in the filters and, therefore, to time-consuming and sometimes cumbersome cleaning [76].

The different stages that seawater desalination with the RO system goes through are outlined below [72,84,85]. It starts with the collection of seawater from a collector tower, an accumulator bilge, and, finally, a seawater drive system. Once the seawater is obtained, pre-treatment is carried out using a mixing and flocculation chamber, open filters (anthracite sand), and a cartridge filter. The water is then passed through high pressure + RO. The RO desalination system of the desalination plant is configured in production units and reserve units consisting of the following elements: High pressure pump—Physical process water outlet—Energy recovery—Booster pumps. Then, in the desalination plant, the water goes through post-treatment and remineralization, where minerals are injected to obtain multipurpose water. This process requires elements such as: A CO_2 dosing system—Lime dosing system—Lime saturation system—Storage system. Finally, the last stage is reached, where a type of water that can be used for domestic consumption, irrigation, and water for mining and industry is obtained.

The information and instruments necessary for the development of this objective were collected and compared. It is not intended to be an exhaustive economic–financial study but rather a guideline for understanding the costs related to these desalination plants. For this purpose, material from different sources related to the initial investment, costs, and depreciation involved in the installation of a desalination plant in the Coquimbo region (Chile) was triangulated [86–88]. For this, the following assumptions were used for the calculation of the costs associated with the economic evaluation:

- The initial investment is estimated to be approximately USD 181,000,000 (as an estimate on 11 November 2022, USD 1/883.3 Chilean pesos). This amount is estimated on the basis of a project of similar characteristics evaluated by the national company "Aguas del Valle" [89] between 2021 and 2022 in the sector known as "El Panul" in the Coquimbo region, which covers a desalination plant capable of producing between 200 and 600 L per second, with a maximum of 1200 L per second.
- For the calculation of depreciation, tangible assets are considered; these assets were estimated from the article "Works and irrigation infrastructure projects for the provinces of Petorca, Limarí and Choapa" delivered by the Ministry of Public Works in 2015 [90]. The RO desalination plant, the seawater lifting plant, and the seawater impulsion or conduction system are considered for the calculation. Table 3 shows, in detail, the unit values of each asset and their assumed useful life.

Table 3. Depreciation of tangible project assets (expressed in USD).

	Unit Value	Full Value	Amount	Useful Life	Annual Depreciation	Accumulated Depreciation	Residual Value
Desalination Plant	78,535,039	-	1	20	3,962,751	39,267,519	39,267,519
Lifting Plant	20,057,738	200,577,380	10	10	20,057,738	200,577,380	-
Drive and Conduction System	94,097,135	470,485,678	5	10	47,048,567	470,485,678	-
-	-	-	-	-	**71,033,057**	-	-

- The estimation of fixed production costs is based on research on the design of a desalination plant with an RO system considering the geography of the territory of Chile [91]. Regarding these costs, they are distributed in three categories: first, the costs for the remuneration of each worker are detailed; second, the maintenance costs are presented, which include the costs for civil works and equipment; finally, the costs assigned to other expenses, such as office expenses, insurance, security, consultancy, and the environment, are detailed. Tables 4–6 show the details of the fixed costs to be considered for production.

Table 4. Costs for the remuneration of each worker (amounts expressed in USD).

Workers	Amount	Monthly Salary	Annual
Director	1	4860	58,320
Operator	20	817	9804
Biologist	2	973	11,676
Chemical	3	966	11,592
Engineer	3	1550	18,600
Office Worker	4	2491	29,892
Security Guard	4	449	5388
Operation	-	-	**419,820**

Table 5. Maintenance costs that include expenses for civil works and equipment (amounts expressed in USD).

Maintenance	Investment	Total Annual
Civil work	6,792,709	679,271
Equipment	27,170,837	2,717,084
Totals	-	3,396,355

- The estimation of variable production costs is based on an article provided by the Library of the National Congress of Chile in 2017 [92], which indicates the variable costs necessary for the use of desalinated water. These costs are distributed in three categories, among which the value related to the high energy cost demanded by a desalination plant stands out, which means that it is not something to be neglected and, on the contrary, a key element to evaluate. For more details, the specific values are detailed in Table 7.

Table 6. Costs assigned to other expenses such as office expenses, insurance, security, consultancy, and the environment (amounts expressed in USD).

Others	Total Annual
Office expenses	2038
Insurance	6113
Security	4076
Consulting	2038
Environment	15,283
Totals	29,548
Total estimated fixed costs (amounts expressed in USD)	**3,845,723**

Table 7. Variable costs associated with production (amounts expressed in USD).

	Costs
Energy	8,866,701
Chemical Products	243,405
Spare Parts	328,314
Total Variable Costs	**9,438,420**

- The transfer costs depend on the trucks that transport drinking water to the rural sectors, taking into account that, according to the Public Account of the Regional Government of Coquimbo (2020), more than 26 thousand families were supplied with water in cistern trucks. The investment for the rental of these vehicles amounted to USD 3,340,623, with a fleet of 75 tank trucks. However, the figures provided by "Aguas del Valle" (2022) indicate that the value of a cubic meter of water is USD 1. For the transfer of water, the use of 30 tank trucks is required, and the value of transporting a truck is USD 10, so multiplying these values gives us a monthly total of USD 9.153, which leads to its annual cost of USD 130,699 (Table 8).

Table 8. Transport costs for water distribution (amounts expressed in USD).

Average Pond Capacity Litters	Average Value m^3	Daily Necessary Trucks	Truck 1 Value	$ Total $ Total Daily Trucks	$ Total Monthly Trucks	$ Total Trucks per Year	With VAT
10,000	1	30	10	305	9153	109,831	130,699
-	-	1	Truck	10	m^3	-	-
-	-	30	Trucks	300	m^3	-	-

- An estimate is made of the potential monetary income that can be obtained from the sale of NaCl. It is inferred that 864,000 kg of NaCl are collected daily, of which 50% of the total, i.e., 432,000 kg, will be sold. In subsequent years, sales are projected to increase by 5% per year. It is estimated that each kilogramme collected will be sold at a market price of USD 0.57 net, so the total daily value is USD 246,240 or 7,387,200. This results in an annual income of USD 88,646,400 (calculated on a 360-day basis), as shown in Table 9.

Table 9. Estimated income from the sale of salt (amounts expressed in US dollars).

Sale of Industrial Salt	Value (kg) *	Month (kg) *	Annual Value
432,000 kg * NaCl/day	0.57	7,387,200	88,646,400

* kg = abbreviation of kilogram (Standard International System of Units).

- Due to the previously specified assumptions, it was possible to carry out the projected Cash Flow for 10 years, where we can highlight that even when a large investment is necessary, the recovery years do not amount to more than 2 years, for what we consider to be an investment in the short term. All this is reflected in Table 10.

Table 10. Cash flow of the desalination project for the Coquimbo region, Chile (amounts expressed in USD).

	Year 0	Year 1	Year 2	Year 3		Year 4
(+) Sales Income (salt)		88,033,510	92,435,186	97,056,945		101,909,793
(+) Fixed Cost of Operation		−3,822,085	−3822.85	−3822.85		−3822.85
(−) Variable Cost of Production		−9,438,420	−9,438,420	−9,438,420		−9,438,420
(−) Transfer Expense		−130,699	−130,699	−130,699		−130,699
(−) Depreciation		−71,033,058	−71,033,058	−71,033,058		−71,033,058
(=) Profit before Tax		3,609,247	8,010,923	12,632,683		17,485,530
(−) Taxes (27%)		−974,497	−2,162,949	−3,410,824		−4,721,093
(+) Profit After Tax		2,634,750	5,847,974	9,221,858		12,764,437
(+) Depreciation		71,033,058	71,033,058	71,033,058		71,033,058
(+) Residual Value		-	-	-		-
(−) Plant Investment	−1,810,003,736	-	-	-		-
(=) Cash Flow	−1,810,003,736	799,100,808	90,739,929	102,109,457		114,047,462
	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
(+) Sales Income (salt)	107,005,282	112,355,546	117,973,323	123,871,990	130,065,590	136,568,869
(+) Fixed Cost of Operation	−3,822,085	−3822.85	−3822.85	−3822.85	−3,822,085	−3822.85
(−) Variable Cost of Production	−9,438,420	−9,438,420	−9,438,420	−9,438,420	−9,438,420	−9,438,420
(−) Transfer Expense	−130,699	−130,699	−130,699	−130,699	−130,699	−130,699
(−) Depreciation	−71,033,058	−71,033,058	−71,033,058	−71,033,058	−71,033,058	−71,033,058
(=) Profit Before Tax	22,581,020	27,931,284	33,549,061	39,447,727	45,641,326	52,144,606
(−) Taxes (27%)	−6,096,875	−7,541,447	−9,058,246	−10,650,886	−12,323,158	−14,079,043
(+) Profit After Tax	16,484,144	20,389,837	24,490,814	28,796,840	33,318,168	38,065,562
(+) Depreciation	71,033,058	71,033,058	71,033,058	71,033,058	71,033,058	71,033,058
(+) Residual Value	-	-	-	-	-	39,267,519
(−) Plant Investment	−10,075,796	-	-	-	-	-
(=) Cash Flow	**116,506,570**	**139,744,016**	**153,563,748**	**168,074,466**	**183,310,722**	**238,576,309**

- In this case, it is the overall profitability of the industry (market) in the country where the investment will be made, i.e., Chile. This rate includes the country risk and the risks of the specific industrial sector of the project. Ref. [93] shows that Rm estimates are higher in countries with higher country-risk levels, so in developing countries, investors demand greater returns as compensation for greater risks. To estimate RIndustry Chile, we use the CAPM and find that the expected return of an industry is equal to the risk-free return (Rf Chile) plus a risk premium equal to the difference between the market return of the specific country (Rm Chile) and the risk-free rate, multiplied by the β coefficient of that industry in the USA (βindustry USA) (Equation (2)).

- In this equation, it is assumed that the β coefficients of the different USA industries (generally computed using the S & P500 as a proxy of the Rm) are approximately the same as the industrial βs that would result in other countries if the Rm of each country were to be used in the calculation [94]. This is because obtaining estimates of the industrial βs in developing countries may be nearly impossible when there are not publicly traded companies. Alternatively, the estimate may turn out too unreliable if the number of companies in the industry is too low. This is the reason why we use, as proxies, the β estimates as obtained from data of stock exchanges with enough liquidity and international integration as the Americans.
- For the determination and calculation of the discount rate, a series of steps were carried out. First, to calculate the cost of equity, we used the "Capital Asset Pricing Model" (CAPM) formula as presented, as this is the one chosen to calculate the discount rate for this project. This model is used to calculate the expected returns on assets while including the risk and cost of capital [95].

$$\text{CAPM} = \text{R} = \text{Rf} + (\text{Rm} - \text{Rf}) \times \text{Beta} \quad (1)$$

where:

- R: The expected return
- Rf: The risk-free rate
- Rm: The expected market return
- Beta: The systematic risk of the assets.

Then, each term of the CAPM formula is calculated to obtain the cost of equity. The risk-free rate for Chile is calculated using the following equation:

$$\text{Rf Chile} = \text{Rf us 10\_year T-Bond} + \text{Country Default Spread} \quad (2)$$

The value of Rf us 10_year T-Bond is obtained from the page Fred, giving a value of 4.1%, and the Country Default Spread is obtained from the following Table 11, giving a value of 0.60%.

Table 11. Country default spreads from Moody's (January 2022) [96].

Country	Moody's Rating	Adj. Default Spread
Canada	Aaa	0.00%
Cape Verde	B3	5.53%
Cayman Island	Aa3	0.51%
Channel Islands	Nr	0.72%
Chile	**A1**	**0.60**

Replacing the data in Equation (2), the estimated risk-free rate for Chile is 4.1% + 0.60% = 4.70%.

To calculate the expected market return, the following equation is used:

$$\text{Rm (semi-annual)} = 53.71 - 10.47 \times \ln(\text{CCRchile}) \quad (3)$$

where the estimate of CCRchile is 77.3%. Replacing the data, we obtain an Rm Chile of 53.71 − 10.47 × LN (77.3) = 8.19% semi-annual, i.e., 16.38% annual rate. Regarding the beta, this is calculated using the table Betas by sector (United States), as shown below in Table 12:

Table 12. Betas by sector in the United State. [97].

Industry		Betas by Industry
Name of Companies	Number of Companies	Beta
Chemistry (Basic)	35	1.16
Chemistry (Diversified)	4	1.50
Chemistry (Specialty)	81	1.10
Coal and Related Power	18	0.92
Computer Services	83	1.20

The industry that most closely resembles what is required—in this case, the sale of industrial salt—is the basic chemical industry, so the estimate of the beta coefficient would be 1.16. By replacing the data in Equation (1), the cost of equity will be 18.25% (Equation (4)).

$$\begin{gathered}\text{CAPM} = \text{R} = \text{Rf} + (\text{Rm} - \text{Rf}) * \text{Beta} \\ \text{Replacing the data in the equation} \\ 18.25\% = 4.7\% + (16.38 - 4.7\%) \times 1.16\end{gathered} \quad (4)$$

Once the cost of equity is obtained, we proceed to find the US risk premium according to the life stage and the size of risk capital (see Table 13) [56,98–100].

Table 13. Heuristic method for estimating the cost of capital (risk premium).

Heuristic Method for Estimating the Cost of Capital (Risk Premium 'RP')		
Category	Stage of life—Size of the enterprise that would implement the project under evaluation	RP
1	Microenterprises of one or two people and less than 2 years in operation. In the US, investors typically require average returns of around 70%.	58%
2	Start-up. Microenterprises that rely on the special skills of one or two people. They have less than 10 workers and may be managed by a single professional. In the United States, investors typically require average returns of around 52%.	40%
3	Small companies. They employ between 11 and 49 employees and are often family-owned. In the US, investors typically demand average returns of around 41%.	29%
4	Venture Capital. Medium-sized companies with between 50 and 250 professionals. In the US, investors typically demand average returns of around 35%.	23%
5	Exit stage. Medium-sized companies with conditions to go public. They have stable past earnings and a fairly predictable future. In the US, investors typically demand average returns of around 32%.	20%
6	Public company. These are large companies (more than 250 employees). Part of their funding is public, and their finances are open to the public. The total return of these companies in a given country represents, approximately, the Market Return (MR). They are established companies that have a strong commercial position, are well financed, and have a depth of management, whose past earnings have been stable and whose future is highly predictable. In the US, investors typically demand average returns of around 12%.	**0%**

For this case, the industry estimated to be marketed corresponds to category number 6, since it was based on the assumptions of a public investment.

Once the risk premium has been obtained (in this case, 0%), the return on equity is calculated using the following formula:

$$\text{R Chile SME} = \text{R Chilean industry} + \text{“RP” Risk premium} \quad (5)$$

$$18.25\% = 18.25\% + 0\% \quad (6)$$

The discount rate used to determine the NPV of the project in question is 16.15%. Finally, with everything seen above, it is possible to calculate the minimum return that a company must achieve on its assets (CCPP), giving a CCPP of 18.25%.

With the data obtained from the cash flow and the discount rate, it is possible to calculate the NPV, IRR, and IRR indices necessary to evaluate the profitability and viability of the project in question. The respective values are shown in Table 14 below.

Table 14. Calculation of the NPV, IRR, IRR, and PRI. Discount Rate.

Discount Rate	**18.25%**
NVP	USD 349,695,775
IRR	54%
IRR	3.70

3.2. Develop Proposals for the Use of Waste from the Freshwater Desalination Process Based on the Circular Economy

Once the feasibility of implementing a desalination plant through the RO process has been analyzed, its affordable cost, proposals, and/or solutions related to the waste caused by the transformation of seawater to freshwater are elaborated.

As already observed, salt is the main waste produced by desalination plants. It is a white, crystalline substance that is very soluble in water and is abundant in nature in the form of large solid masses or dissolved in seawater and in some lagoons and springs. On average, a desalination plant extracts 60% of freshwater suitable for human or industrial consumption, while the other 40% corresponds to brine, which, as its name suggests, is a concentrate of NaCl that is highly toxic to the environment and to marine biomass [22,75].

In terms of the processes used for the removal of this waste and/or conventional brine, disposal methods are: discharge into the sea, injection into deep wells, evaporation ponds, and land application. Their environmental impacts are increased salinity, destruction of the marine micro-organism ecosystem, discharge of heavy metals by corrosion (Cu, Fe, Ni, Cr), and ecological and socio-economic damage. Thus, effective, efficient, and competent brine management is absolutely necessary [22,38,43].

The easiest potential solution for disposing waste salts (brine) is in the industrial sector. The brine is used in large quantities to de-ice and remove snow on major roads and city roadsides, but with very damaging effects on the roads and the surrounding ecosystem [95]. To measure the magnitude of the volume of brine transported and used on roads and surrounding streets, in Minnesota (United States) alone, it is estimated at about 403,600 tons [101]. In other words, an added value is given with an industrial use to the greatest waste from the desalination of seawater. However, despite the intensive use that it is given in some countries to help melt snow and ice, this process is highly polluting, and, therefore, it is still not a sustainable solution, because the NaCl returns to the environment with other chemical components that are added to the salt, which damages the ecosystem and infrastructures that are treated with this product.

Considering this crucial point, a new challenge presents itself with an opportunity to innovate [102] and, with this, intensify the development of a potential solution to brine pollution, which would greatly benefit the various ecosystems invaded by this problem while favouring a new sustainable industry for the region and Chile. Considering a 10-year projection, the scheme offers excellent economic prospects, with a cash flow that reflects the recovery of the initial investment and establishes a surplus over profitability. In other words, a virtuous circle is generated, where fresh water necessary for the region is produced, a resource (waste) such as NaCl, which, in excess, is toxic for the environment, is used, and at the same time, the water extraction and treatment areas are freed from stress in a circular economy.

3.3. Potential Solution Proposed through the Use of the Microalga Dunaliella salina

In order to favor a higher profitability of the desalination industry, it is proposed to generate a product that provides an added value to the market using the brine waste from the wastewater. We are referring to the cultivation in controlled environment microalgae that are tolerant to high concentrations of NaCl on a large scale and suitable for human consumption due to their β-Carotene content. Microalgae are a family group of photosynthetic species that are not completely visible to the human eye [103]. For some time now, numerous biotechnological applications have been developed with the implementation of these microalgae, as they have many industrial purposes, such as in wastewater treatment and in the production of biodiesel and probiotics [56,100,104,105]. In addition, microalgae can generate several natural compounds and pigments such as carotenoids that are used in the pharmaceutical, cosmetic, and food industries [53,106]. Among carotenoids, one of the most sought-after compounds is β-carotene, astaxanthin, and vitamin B and lutein [104,107].

Overall, the proposed use of *Dunaliella salina* microalgae for treating brine waste generated by desalination plants offers an opportunity to create a business model that takes advantage of this microalga's potential to produce high-value products such as β-carotene, fatty acids, and antioxidants. However, careful consideration of the cost of the extraction process, the cost of producing the desired value-added products, and the potential market demand for these products must be considered before beginning the development of such a business model.

Due to the population growth and global warming events, the use of seawater RO to obtain freshwater is increasing rapidly. A sustainable method with low environmental impact is limited to brine management with a high salt content. This brine is released during the process.

Among the microalgae that produce large amounts of these carotenoid pigments and, at the same time, withstand high concentrations of brine is *Dunaliella salina*. This is a green microalga recognized as an excellent producer of β-Carotene, a type of carotenoid which has properties as an antioxidant and precursor of vitamin A and is used in products as a food supplement for cancer protection and immune system enhancement and used in cosmetics and in the food and animal industries [107–110]. β-carotene contributes to color development by adding it to dairy products such as cheese and even some margarines. It is used in poultry feed and to improve the color of meat and egg yolk. However, β-carotene concentrations from green microalgae have a higher efficiency compared to other synthetic or chemical production methods [46]. β-carotene is present in numerous organisms such as green leafy plants, fruits, vegetables, and some species of microalgae and is used in human and animal food, as well as in the salmonid industry as a colorant [107]. This pigment follows the general pattern of chloroplasts in all higher plants, i.e., lutein, β-carotene, violaxanthin, neoxanthin, zeaxanthin, β-cryptoxanthin, and anteraxanthin [108].

Economically, β-carotene has a market price of between USD 300 and USD 3000 per kg, depending on the demand, its source, and its availability. The global β-carotene market is projected to grow at a CAGR of 3.93% during the forecast period of 2020–2025. In 2018, the market for this dye reached MM USD 9.6 [109].

From this perspective, it becomes a great challenge to use wastewater from desalination plants in a bio-circular way, taking advantage of brine residues for the cultivation of the green microalga *Dunaliella salina*, because this microalga withstands the high concentrations of salts such as brine and other minerals very well [110,111]. For the cultivation of *Dunaliella salina*, a salinity of 1.5–3 M NaCl is used [112]. The intention is cultivating the microalgae in a closed system in order to avoid returning the brine to the sea and to take full advantage of this resource at a very low cost. This is an interesting element because in traditional open sea cultivation, seawater is saturated with the addition of a large amount of salts to increase the NaCl concentration, generating a cost of more than one-third of the total budget of microalgae production, which could be saved by using wastewater from desalination plants but in a closed circuit to avoid injecting salt into the open sea.

The green microalga *Dunaliella salina*, in order to produce large amounts of the pigment β-carotene, needs to be in a highly saline environment such as the brine that is discarded from desalination plants. Cultures are already carried out using flat plate photo bioreactors [113–128]. Sustainable management could be realized with the production of β-carotene from microalgae, with high added value in the field of the circular bio economy.

In order to better substantiate this process of the cultivation of the microalga *Dunaliella salina*, a SWOT matrix is presented to assess the strengths, weaknesses, opportunities, and threats related to the implementation of this process.

It is also proposed that, with the implementation of the SWOT analysis, the production of algae pigments such as β-carotene on a commercial scale should be targeted, and key economic, strategic, and environmental elements should be considered from the acquisition of each step of production to the final product to be sold on the market. This is reflected in Figure 3 below.

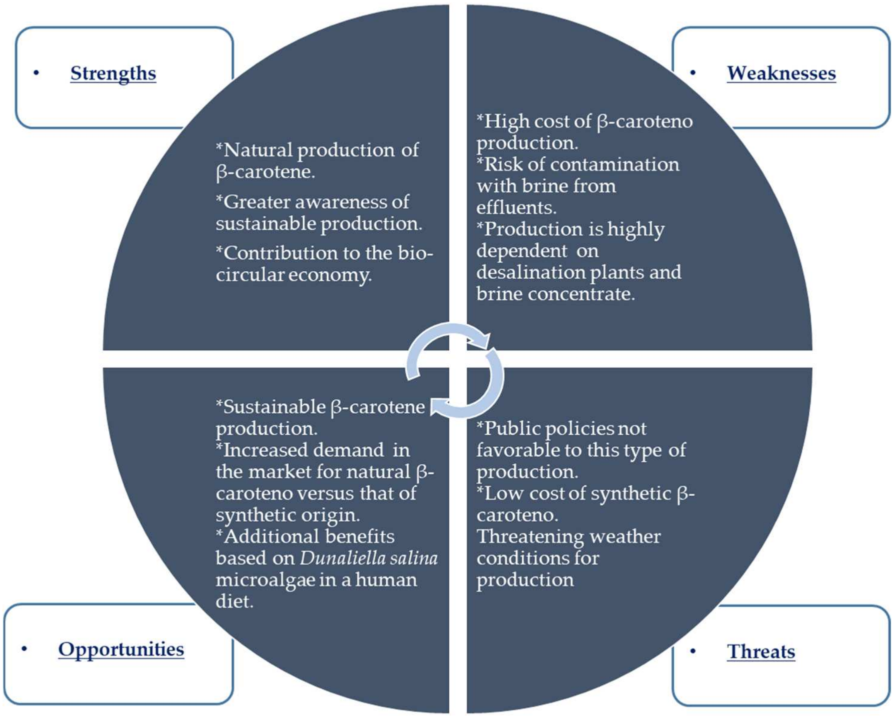

Figure 3. SWOT: Strengths, Weaknesses, Opportunities, and Threats analysis of the project.

It is fair to clarify that this proposal was not intended to be an exhaustive analysis related to the microalga *Dunaliella salina* but rather a hint of an exploratory channel that will require more in-depth scientific studies.

4. Conclusions

In order to quantify the facts studied, it is estimated that more than 50 million people in the world lack freshwater for consumption and basic needs, while it is estimated that by 2050, at best, about 7 billion people in 60 countries will suffer from water scarcity of some kind, while at best, about 2 billion people in 48 countries will be affected by water deficiency. The data indicate that a proposal must be innovated to address the hydric scarcity issues that afflict Chile and the world.

This makes it necessary to think seriously about the development of new sources of water supply that are environmentally sustainable over time in order to, among its main missions, reduce the gap between the number of people without access to drinking water and those who have access to this resource, seeking greater equity in its availability.

Based on this, we believe that the seawater desalination plant in the region of Coquimbo (Chile) is an imperative need, and the one that is the most suitable due to its economy, efficiency, and proven technology is the RO. This RO process is relevant because it offers the finest filtration currently available; this is because it has no pores in its structure, allowing for the rejection of most dissolved and suspended solids while preventing the passage of bacteria and viruses, obtaining pure and sterilized water suitable for human and animal consumption.

After the financial analyses carried out, it is possible to reflect that the implementation of a desalination plant in the Coquimbo region is viable since the NPV of the project for the installation of a desalination plant in the IV region showed a positive value of USD 349,695,776. This indicates that there will be a recovery of the initial investment and a surplus over the required return. By obtaining an NPV greater than 0, it can be concluded that the research project is profitable and will in turn generate benefits, such as greater wealth, at the time of deciding to sell the desalination plant. It is relevant to point out that the proposed business model is tempting because of the proposed sale of industrial salt, which, having a low price implemented by the work team, achieves high revenues. This is because the amount extracted from the desalination process is around 40% per liter of seawater added to the proposed cultivation of the microalga *Dunaliella salina*.

Note that the IRR in the study of this project has given a value of 54%, which means that the Internal Rate of Return is higher than the discount rate that was calculated for the operation with the NPV. This indicates that the investment project is accepted with confidence because the internal rate of return will be higher than the minimum rate of return required for the implementation of the study. The PRI (Period of Return on Investment) yielded an estimated 3.7 years, which means that the initial investment of the plant will be recovered in approximately 3 years and 7 months. This is considered a short and reasonable time considering the positive effects and benefits that the project will bring.

Finally, it can be inferred that, for the proposed project, further interdisciplinary scientific studies should be carried out to strengthen and derive new production processes that enhance the cultivation of the microalga *Dunaliella salina* to validate and reaffirm its viability, since, to our knowledge, there are no facilities that produce β-carotene on an industrial scale using brine or the wastewater generated in a desalination plant. However, when examining the SWOT analysis of the proposed system, it is foreshadowed that sustainable natural β-carotene production could be achieved, generating an interesting circular bio-economy, especially in countries where the climatic characteristics are suitable for the cultivation of microalgae such as *Dunaliella salina*.

It is possible to solve the problem of brine produced by desalination plants through an innovative and environmentally sustainable business model by adding value to the waste by the confined cultivation of the microalga *Dunaliella salina* that tolerates an environment with a high NaCl concentration. This innovation based on the principle of a bio-circular economy efficiently solves the problem of brine waste being returned to the sea, which, due to its quantity and high concentration, produces toxic effects on the environment and the surrounding biota due to salt stress in an area close to desalination plants. At the same time, for protecting the environment, new business opportunities are generated for the region through the cultivation and commercialization of the microalgae, either unprocessed or by adding value by transforming it into b-carotene. Meanwhile, the surplus of this waste is marketed to numerous industries that require it (road de-icing, petrochemicals, bleach synthesis, soap making, food preservation, and agricultural use).

Given the magnitude of the investments presented and the ever-increasing cost of energy, it could be said that one weakness of the project is related precisely to this item, since an in-depth study should be made of the existing possibilities of generating energy from the desalination plants that contribute to their operation. However, it is important to retain this point so that, together with the microalga *Dunaliella salina*, it can be an interesting alternative for future studies in greater depth. At the same time, one of the main advantages lies in bringing to light the economic use of the most important waste, which is brine through the use of *Dunaliella salina*. From this microalga, it is possible to demonstrate that added value can be produced with b-carotene, other types of lipids, and vaccines to restore contaminated environments.

Therefore, the novelty of this research comes from two aspects. On the one hand, it considers the valuation of the investment, the costs, and the depreciation associated with the installation of a desalination plant in the north of Chile. On the other hand, it analyzes the importance of brine waste management, and at the same time, it raises the development of a product with high global demand in the industry of nutraceuticals such as β-carotene from brine and the microalga *Dunaliella salina*. At the same time, it helps maintain the saline balance. This is extremely important for the different ecological communities that thrive near aquatic dumping sites.

The most complex points lie in the difficulties that developing countries have in financing these large projects, whether for the algae or the desalination plant. This makes it difficult to meet the goals of access to fresh water.

5. Challenges and Prospects

Desalination plants and the microalga *Dunaliella salina* offer potential solutions to address water scarcity and meet increasing demands for freshwater. However, there are several challenges that need to be addressed to maximize their benefits.

One of the main challenges faced by desalination plants is the high cost of implementing and maintaining them. These costs can be attributed to the high energy requirements, material and equipment costs, and the disposal of concentrated brine. The disposal of brine can also lead to environmental concerns, including harm to marine life and the degradation of aquatic ecosystems.

Another challenge is the variability of feed water quality, which can affect the efficiency of desalination processes. Feed water quality can vary based on factors such as the location, season, and climate change, which can impact the performance of desalination plants and the quality of the water produced.

In the case of the microalga *Dunaliella salina*, challenges include the optimization of growth conditions, harvesting methods, and the development of efficient extraction techniques. The variability of environmental conditions and the competition with other microorganisms can also affect the growth and productivity of microalgae.

Despite these challenges, there are several prospects for the future of desalination plants and the microalga *Dunaliella salina*. Advances in technology and innovation can reduce the cost of desalination and improve the efficiency of microalgae growth and harvesting. For example, the use of renewable energy sources, such as solar and wind power, can reduce the energy requirements of desalination plants. Similarly, the development of high-efficiency photo bioreactors and cultivation techniques can improve the productivity and yield of microalgae.

Furthermore, the use of waste streams from desalination plants as a source of nutrients and minerals for microalgae cultivation can create a closed-loop system that maximizes the benefits of both technologies. This approach, known as the bio-circular economy, can reduce waste and environmental impacts while enhancing resource efficiency.

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