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Innovative solutions for valorization of desalination brine

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A B S T R A C T

Desalination is becoming increasingly important to meet the growing demand for freshwater. However, a major drawback of this technology is the production of hypersaline brine. This by-product contains salts and contaminants that have been removed during the desalination process, including antiscalants, cleaning agents, heavy metals, and organic compounds. Instead of disposing of this brine and causing environmental harm, new strategies should be developed to transform brine from a burden into an opportunity with environmental and economic benefits. Brine can harbor halotolerant and halophilic microorganisms, making it a valuable resource for studying microbial diversity, adaptations and exploring untapped biotechnological opportunities in pharmaceutical, industrial, and ecological fields. We propose two strategies of innovation: (i) using brine to cultivate micro- and macro-organisms, both of which can create circular economy models tailored to global and local needs. (ii) In addition, the amount of brine generated by desalination plants can be reduced by integrating or coupling them with biodesalination modules. These modules would harness halotolerant and halophilic organisms to retain and assimilate salts, reducing the environmental impact of desalination.

1. Introduction

Desalination is not a recent method for obtaining potable water; sailors have practiced seawater desalination for centuries (Greenlee et al., 2009). However, it has only seen significant expansion and industrialization in the past half century (Elimelech and Phillip, 2011). Desalination techniques are used for removing salt and other impurities from seawater or brackish water to generate freshwater for various purposes, including drinking, irrigation, and industrial applications (Kucera, 2014). A 2019 report from the International Desalination Association (International Desalination Association; Ihsanullah et al., 2021) notes that there are 19,744 desalination plants in more than 150

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countries worldwide (of which 48 % in Middle East and North Africa - MENA) (Eke et al., 2020), supplying fresh water to over 300 million people. The total output of desalinated water has seen significant growth, increasing from around 25 million cubic meters per day in 2000 to approximately 95 million cubic meters per day in 2019 (L. Gao et al., 2021). According to the United Nations, nearly 7 billion people across 60 countries will experience severe water scarcity by 2050 (Ihsanullah et al., 2021).

Currently, desalination technologies fall into two main categories: thermal and membrane-based methods (reviewed in Curto et al., 2021 (Curto et al., 2021), Harby et al., 2024 (Harby et al., 2024) and Cai et al., 2023 (Cai et al., 2023)). Thermal desalination is highly energy-intensive due to the substantial energy required for water phase changes, owing to water's high enthalpy of evaporation. The principal thermal desalination techniques include multi-effect distillation (MED), multi-stage flash distillation (MSF), and thermal vapor compression (TVC). Membrane desalination methods use high pressure of motor pumps to separate water from highly concentrated saline solutions. As a result, membrane methods are dependent on electrical power. Membrane methods are primarily classified into reverse osmosis (RO), electrodialysis (ED), and nanofiltration (NF). While RO systems generally produce lower-quality freshwater compared to thermal processes, they are considered cleaner and safer, operating at lower energy levels, temperatures, and pressures. However, membrane systems can be expensive for large-scale applications, and membrane materials may degrade over time due to excessive wetting. To enhance RO performance and lower water production costs, hybrid systems that combine RO with thermal methods, such as TVC, MED, or MSF, are being developed. Among these, RO-TVC, RO-MED, and RO-MSF configurations are the most common. Globally, RO plants account for 68.7 %, MSF 17.6 %, MED 6.9 %, NF 3.4 %, ED 2.4 %, and other methods making up the remaining 1.0 % (Jones et al., 2019).

In general, the ion concentration of brackish water is much lower than that of seawater and therefore brackish brine has a lower ion concentration and lower total dissolved solids than seawater. For seawater brine, there are also variations in ion concentrations and total dissolved solids depending on the location of the plant, technology and the type of intake, open seawater or beach well (Supplementary File 1).

During the desalination process, seawater is split into two components: the permeate (desalinated water) and the concentrate (effluent, known as brine). Desalination brine contains residual salts, minerals, and chemicals (Jones et al., 2019). Recent estimates suggest that global brine production exceeds 140 million m^3/day (Jones et al., 2019). This figure is anticipated to rise further in the future due to growing water scarcity and an increased demand for desalination. The latter is increasing particularly in freshwater-scarce regions such as MENA, which host around half of the world's saltwater desalination operations. Brine disposal can negatively affect the environment, so finding ways to manage its use across diverse applications can yield positive environmental benefits (Panagopoulos et al., 2019), and can also generate economic value. Indeed, the use of desalinated water is associated with higher environmental concerns by the general population than the use of recycled water (Dolnicar and Schäfer, 2009). Additionally, the use of desalinated water for irrigation is also associated with environmental concerns, of which the significant majority relate to brine disposal (Ghermandi and Minich, 2017). Consequently, a technological breakthrough is needed to tackle the increasing issue of brine generation. This would address environmental concerns, improve the acceptance of desalination in regions outside MENA from policy, scientific, environmental and general population perspectives. All of this motivated this study, where we asked the questions that are most commonly asked in discussions on the possibility of expanding desalination operations and increasing the acceptability of the use of desalinated water. The questions were addressed under two categories:

1. Environment: What is brine composed of? Where does it go (environmental fate) and how does it affect the environment?
2. Valorization of brine: What are the possibilities to valorize brine and decrease its impact on the environment? We focused on the biotechnological solutions involving macro and microorganisms, as well as biodesalination processes, all of which represent an innovation and opportunity to establish circular solutions, which can positively influence the acceptability from the scientific, social and policy levels due to the possibility of novel commercial applications, investments and job creation.

2. Materials and methods

A structured narrative literature review was conducted to synthesize current knowledge on micro- and macro-organisms that can be cultivated using desalination brine effluent within the framework of a circular bioeconomy. To identify relevant studies, major scientific databases were searched, including Scopus, Web of Science, and Google Scholar. For plant-related studies, additional data were cross-referenced using the specialized eHALOPH (https://ehaloph.uc.pt) database.

The search strategy combined organism-specific and thematic keywords using Boolean operators. The following organism-specific terms were used: "microorganism", "halophile", "saline", "bacteria", "cyanobacteria", "fungi", "microalgae", "macroalgae", "halophytes", "*Artemia salina*", "*Tilapia*", "diversity". The thematic keywords included: "desalination brine", "salt tolerance", "salinity stress", "cultivation", "biomass production", "bioproducts", "biosaline agriculture", "aquaculture", "hypersaline biotechnology", "halophilic crops", "halophilic farming", "biodesalination", "sustainability desalination".

The inclusion criteria were as follows: studies on species able to thrive under high salinity, or cultivated under saline, brackish, or hypersaline conditions; publications describing the use of such organisms in agriculture, aquaculture, bioremediation, bioenergy, or high-value product manufacturing; papers including physiological, biochemical, or techno-economic data relevant to cultivation or application. Only publications containing non-redundant relevant data were cited. Some market reviews were included to reflect the demand, economic value, and scale-up limitations for bioproducts that can be produced using desalination brine. Studies focused solely on molecular or genomic data without context for cultivation or practical applications were excluded.

3. Environmental fate of rejected brine

Several common methods exist for managing desalination brine. The most economical and widely used approach, employed by over 90 % of global seawater plants, involves discharging brine into surface water bodies, such as rivers, lakes, wetlands and coastal areas, after adequate dilution, to minimize localized impacts on the ecosystems (Panagopoulos et al., 2019). Brine disposal into wastewater collection systems or at the outfall of wastewater treatment and power plants is also common, particularly in small-scale desalination units (Voutchkov, 2011). In both cases, the brine is eventually diluted in larger water volumes, becoming part of the aquatic environment. Some desalination facilities use evaporation ponds to handle brine, leaving behind concentrated salts and minerals (Ahmed et al., 2000). This method effectively reduces brine volume, which can be particularly applicable in arid regions, and minimizes environmental impact when the pond base is lined with an impermeable geomembrane. If this is not properly done, brine components can leach into adjacent soils and underlying aquifers (Mohamed et al., 2005). Another widely used method is deep-well injection, which involves placing desalination brine into coastal underground aquifers that are naturally isolated from surrounding water bodies. While there is a slight risk of brine leaking back to the ocean, this approach is generally considered environmentally friendly and cost-effective (Stein et al., 2021).

4. Brine contaminants

Desalination plants are typically located near coastal marine habitats for practical reasons, providing clear socio-economic benefits for humans. However, this proximity can also pose ecological risks to the surrounding marine environments (Panagopoulos and Haralambous, 2020). Despite growing concerns regarding the potential environmental impacts of the growing desalination industry, research on the effects of brine discharge remains limited. When brine is discharged from desalination plants, it often contains elevated levels of nutrients and contaminants acquired during the desalination process, all of which harm marine ecosystems if not properly managed. Among the different contaminants that can be present in reject brine, heavy metals have traditionally been of highest concern. Metals, such as cadmium, cobalt, copper, mercury, vanadium, iron, lead, zinc, copper, and arsenic, may be present from the use of scale inhibitors, which are added at different points of the desalination process or to maintain the desalination facilities. These metals are known to accumulate in marine sediments close to desalination plants (Sadiq, 2002; Ahmad and Baddour, 2014). Studies show that these contaminants decrease in concentration with distance from the brine discharge point, indicating that it acts as a point source of metals pollution.

Besides metals, reject brine may contain various by-products and residues from chemicals used as anti-scaling, anti-foaming and anti-corrosion agents in desalination plants (Ihsanullah et al., 2021; Shokri and Sanavi Fard, 2023). Polyphosphates were the first generation of antiscalants, however they were found to contribute to eutrophication as they are readily hydrolyzed to orthophosphate (AQUA-CSP 2007). Consequently, they were replaced by polyphosphonates and polycarbonic acids (e.g., polyacrylic and polymaleic acids), which are more resistant to hydrolysis. Their discharge levels are generally considered non-hazardous, as they are well below concentrations that could cause toxic or chronic effects in higher organisms (AQUA-CSP 2007). Nevertheless, the use of antiscalants has been shown to influence the composition of bacterial communities in marine environments (Al-Ashhab et al., 2022). There are also concerns regarding more persistent agents, as they may complex with metal ions after being discharged into coastal waters, affecting dissolved metal concentrations (AQUA-CSP 2007). Overall, there is a growing interest in using new antiscalants that are more biodegradable, environmentally friendly and free of phosphorus or nitrogen (Kress et al., 2020).

Several other chemicals are commonly used in desalination plants and may end up in reject brine, as discussed in numerous reviews (Ihsanullah et al., 2021; Shokri and Sanavi Fard, 2023; AQUA-CSP 2007; Tularam and Ilahee, 2007; Lattemann and Höpner, 2008; Chang, 2015; Kim et al., 2015). For instance, polyethylene and polypropylene glycol are two well-known antifoaming agents frequently added to feedwater of thermal desalination plants. Additionally, various chemicals are used for disinfecting seawater intakes and managing biofouling in desalination systems (e.g., RO membranes, heat exchangers), such as chlorine, chlorine dioxide, chloroamines, sodium hypochlorite, sodium bisulfite, sodium hydroxide. More toxic agents including formaldehyde, glutaraldehyde, isothiazole and sodium perborate have also been reported, particularly for disinfecting membranes (Ihsanullah et al., 2021; AQUA-CSP 2007; Lattemann and Höpner, 2008). It is worth noting that free chlorine is the most commonly used disinfectant in desalination plants. Its reaction with organic matter in seawater can produce various genotoxic by-products (e.g., trihalomethanes, haloacetic acids, halonitromethanes, haloacetonitriles), which are of high environmental concern (Kim et al., 2015). Chemicals are also employed to inhibit corrosion and protect the metallic surfaces within desalination systems. They typically include oxygen scavengers that reduce oxygen content in feed water, such as sodium sulfite and bisulfite, hydrazine and its less toxic carbohydrazide substitute. Ferrous sulphate and benzotriazole are added to facilitate the formation of a corrosion-resistant protective coating (Ihsanullah et al., 2021; Shokri and Sanavi Fard, 2023; AQUA-CSP 2007). More recently, a mixture of film-forming and alkalizing amines and polycarboxylates has been introduced for the protection of metallic surfaces in desalination plants (Mahmoodur Rahman et al., 2023). Furthermore, iron-based coagulants, such as ferric sulfate, ferric hydroxide and ferric chloride, are commonly added to seawater intake to improve the removal of suspended and fine particles, while aluminum salts are infrequently used due to their potential to cause fouling of RO membranes (Drami et al., 2011; Kavitha et al., 2019). As a result of filter backwashing in desalination plants, coagulants can end up in the reject brine (Ihsanullah et al., 2021; Chang, 2015; Drami et al., 2011). While most of these chemicals are expected to be present in the reject brine at relatively low levels, the actual impact of combined exposure to various brine contaminants on marine life remains uncertain.

5. Environmental impact

Brine disposal can negatively affect the marine environment due to its high salinity, temperature and the presence of various contaminants (Capó et al., 2020; Benaissa et al., 2020; Omerspahic et al., 2022). However, the latter are often considered less significant and the most adverse effects on marine organisms are typically linked to the localized increase of salinity and the resulting ‘lethal osmotic shock’. This can create unfavorable conditions for marine organisms that are adapted to narrow salinity ranges (Panagopoulos and Haralambous, 2020; Röthig et al., 2023). Consequently, species density and diversity may be affected (de-la-Ossa-Carretero et al., 2016; Kress, 2019), with some species being pushed out of their preferred habitats, leading to alterations in community composition and distribution, increased competition for resources and potential mortality for more vulnerable species (Kelaher et al., 2022). Additionally, brine can lower pH (Noori et al., 2021), which may pose further risks to calcifying marine organisms and reef-associated macroinvertebrate communities (Fabricius et al., 2014).

The temperature of brine produced by RO plants typically does not differ significantly from that of ambient seawater, whereas the concentrate discharged from thermal desalination plants is usually 5–15 °C warmer. This increase in water temperatures can lead to “thermal pollution” at the discharge site. The effects on species distribution due to altered annual temperature profiles at the discharge site are of comparable importance to those caused by changes in salinity. Marine organisms may either be attracted or repelled by warmer water, potentially enabling species with higher heat tolerance to eventually dominate at the discharge site (Miri and Chouikhi, 2005; Lattemann, 2010). In extreme cases, thermal discharge may result in increased mortality among sessile marine species (Pennington and Cech, 2009).

Brine can accumulate on the seabed, forming a persistent layer that disrupts benthic communities. This has been shown to negatively affect sessile invertebrates such as bryozoans (*Microporella* sp., *Smittina* sp. and *Calloporina* sp.), sponges, kelp (*Ecklonia radiata*) and polychaetes (*Pomatoceros taeniata* and *Hydroides elegans*), leading to a significant decline in their populations (Clark et al., 2018; Kelaher and Coleman, 2022). The impact of brine discharge has also been evidenced by the disappearance of echinoderms (i.e., *Paracentrotus lividus* and *Holothurian* spp.) as well as increased leaf necrosis of *Posidonia oceanica* meadows (Latorre, 2005; Fernández-Torquemada et al., 2005; Gacia et al., 2007; Del Pilar Ruso et al., 2007; Sánchez-Lizaso et al., 2008; Cambridge et al., 2019). In addition to *P. oceanica*, brine discharges have been reported to adversely affect the red algae *Rissoella verruculosa* and seagrass meadows of *Cymodocea nodosa* and *Caulerpa prolifera* (Sadhwani et al., 2005). Since seagrasses, corals and other key species provide habitats for numerous associated and dwelling organisms, the effects of brine on these habitat-forming species (Petersen et al., 2018) could significantly impact local biodiversity. Therefore, well-designed desalination operations can help mitigate their potential negative effects on the marine environment (Kelaher et al., 2022).

Non-sessile marine animals can successfully adapt to environmental changes, such as shifts in salinity, by migrating to more suitable habitats (Missimer and Maliva, 2018). While tolerance to hypersalinity varies between different species, most of them avoid salinity above 50 PSU (Remaili et al., 2018). Generally, polychaete and crab species tend to have the highest tolerance, and are able to survive salinities up to 60 PSU for extended periods. Gastropods and bivalves display moderate tolerance, while shrimps, copepods and amphipods are the least tolerant (Omerspahic et al., 2022; de-la-Ossa-Carretero et al., 2016; Momtazi and Maghsoudlou, 2022; Bianchelli et al., 2022). Significant changes in polychaete communities were observed along a transect in front of Alicante desalination plant, Spain, where the families Ampharetidae, Nephtyidae and Spionidae were particularly sensitive to brine discharges (Del Pilar-Ruso et al., 2008). In the same area, a decrease in the abundance of Polychaeta, Bivalvia, Decapoda, Amphipoda, along with an increase in Nematoda was observed near the brine discharge point (Del Pilar Ruso et al., 2007). Conversely, a study at the Las Burras desalination plant, Gran Canaria, revealed a sharp decline in benthic meiofaunal abundance (i.e., nematodes and copepods), with significant changes in their assemblage structure immediately adjacent to the brine discharge point (Riera et al., 2011). At the Carlsbad desalination plant, California USA, a significant increase in epifauna (e.g., Polychaeta, algae, Anthozoa, Echinodermata, Gastropoda) was observed in the immediate discharge area shortly after operations began (Lykkebo Petersen et al., 2019). This change was attributed to the differential survival of organisms in the salinity plume, likely due to reduced predation of polychaetes by larger organisms avoiding high salinity waters, rather than brine-induced toxicity.

Significant effects at the microbial level have been reported in the literature. A study conducted at three desalination facilities along the Israeli coast reported that the abundance and growth efficiency of benthic bacteria were 1.3–2.6 times higher at the outfall area than the background stations, accompanied by notable differences in bacterial community structure (Frank et al., 2019). In the same area, the number of picophytoplankton cells in seawater near the outfall decreased, though this reduction was primarily attributed to elevated temperature rather than higher salinity of the reject brine (Drami et al., 2011). Furthermore, several studies suggest that bacteria are more sensitive to salinity fluctuations than archaea (Mani et al., 2020; Balzano et al., 2021), which, unlike bacteria, can withstand large salinity fluctuations and achieve a stable community structure in a short period of time.

At the level of individual organisms, elevated salinity can impact their cellular and sub-cellular functions, disrupting essential biological processes such as reproduction and growth, particularly in early life stages (Mak and Chan, 2018; Rosner et al., 2023). This can hinder the long-term survival of populations or prevent some species from establishing in certain areas. Moreover, the combination of increased salinity and high nutrient levels from brine discharge may promote harmful algal blooms (Al Shehhi et al., 2014), which can produce toxins harmful to marine life and create "dead zones" with critically low oxygen levels. In addition to toxins, brine pollutants, such as heavy metal leaching from corroded pipelines (Kim et al., 2015; Chowdhury, 2019), can accumulate in the vicinity of desalination plants, exacerbated by accidental oil spills (Ogunbiyi et al., 2023). Additional examples about the effects of desalination brine and elevated salinity on marine life are listed in Table 1, corroborating that these are multifaceted and organism-specific. This underscores the need for careful management and mitigation strategies in desalination practices to protect marine biodiversity.

The environmental impact of specific chemicals present in reject brine is challenging to evaluate. Laboratory studies have shown that commercial antiscalants commonly used in seawater desalination plants (e.g., polyacrylate, polyphosphonate and carboxylated dendrimers) can act as carbon sources, influencing bacterial diversity and community composition in marine environments (Al-Ashhab et al., 2022). Moreover, aquaria experiments revealed that the combined exposure to elevated salinity and a polyphosphonate-based antiscalant had more severe negative effects on the physiology of reef-building corals (including reduced CO_2 uptake and protein content in corals and a decline in their symbiotic microalgae) compared to high salinity alone (Petersen et al., 2018).

Table 1
Observed environmental effects of brine on selected marine species.

Species	Observed Effect	Reference
Posidonia oceanica	Reduced growth/vitality at 39.1 PSU; 50 % mortality at 45 PSU within 15 days of exposure	(Sánchez-Lizaso et al., 2008)
Mytilus galloprovincialis	Developmental abnormalities in >50 % of the larvae exposed to brine of 41.7 - 58.4 PSU	(Quintino et al., 2008)
Diopatra neapolitana	50 % mortality and significant reduction in tissue regenerative capacity after exposure to brine of 42 PSU	(Pires et al., 2015)
Paracentrotus lividus	Egg fertilization failure and abnormal larval development after an exposure to brine of 44 − 52 PSU	(Quintino et al., 2008)
Red abalone, purple urchin and sand dollar	Reduced larval development in 50 % of the population after an exposure to diluted brine of 36.8, 38.1 and 39.6 PSU	(Voorhees et al., 2013)
Mysid shrimp and topsmelt fish	50 % mortality of larvae after an exposure to diluted brine of 47.8 and 61.9 PSU, respectively	(Voorhees et al., 2013)
Sea bream juveniles	Darkened coloration of the body after 30 min exposure to brine of 50 PSU and 25 % mortality after 24 hours exposure	(Iso et al., 1994)

Maintaining balance in marine communities is crucial for a healthy marine ecosystem. Therefore, it is important to exercise caution when establishing desalination plants near sensitive marine ecosystems, such as coral reefs (Petersen et al., 2018), mangroves, seagrass meadows (Gacia et al., 2007) and kelp forests. The key species in these ecosystems are habitat forming marine organisms (that also form sensitive marine animal forests) (Rossi et al., 2022) and changes in their abundance can have significant effects on a plethora of associated and residing marine organisms. Overall, while the impacts of brine discharge and its associated chemicals are typically localized and considered less harmful than other industrial waste, they should not be disregarded. Regular monitoring is essential to assess the tolerance of marine life to desalination effluent, particularly the high content of salt (Fernández-Torquemada et al., 2019), and alternative management strategies are needed to minimize the environmental impact.

6. Innovative solutions to reduce the environmental impact

To minimize the environmental impact of desalination brine, it is essential to explore innovative solutions for its utilization. Additionally, with 5 %−33 % of the total desalination cost attributed to brine disposal (Ahmed et al., 2001), it is crucial to identify value-generating solutions from brine. This can be done through two strategic approaches: (i) use of brine for cultivation of biotechnologically relevant organisms, and (ii) employment of biodesalination technologies to reduce the quantities of brine. By doing so, brine can be transformed into a resource, enabling the implementation of circular solutions that enhance desalination efficiency.

6.1. Brine as a matrix for cultivation of biotechnologically relevant microorganisms

Modern molecular techniques such as metagenomics, metatranscriptomics, and metaproteomics, have provided an opportunity to study brine-associated microbial communities. These methods not only offer a deeper understanding of the diverse microorganisms thriving in saline environments but also reveal valuable insights into their functional potential (Vavourakis et al., 2016; Maseh et al., 2021). In addition to salinity, factors such as temperature, nutrient availability, and pH play critical roles in shaping brine microbial communities. Their functional traits extend beyond environmental roles like nutrient cycling, organic matter degradation, and nitrogen fixation, encompassing a highly valuable secondary metabolism. Halophilic microorganisms, in particular, possess unique metabolic pathways and bioactive molecules (Ortega Méndez et al., 2012; Fabiszewska et al., 2022). Utilizing brine in fermentations and cultivations presents an efficient and cost-effective approach for producing biotechnologically-relevant metabolites, transforming a potential waste into a valuable resource. Below, we highlight some of the most promising organisms for such use.

6.1.1. Bacteria

The unique cellular enzymatic machinery and metabolic traits of bacterial halophiles enable them to balance the osmotic pressure of the environment and resist the denaturing effects of salts (DasSarma and Arora, 2001). Bacterial halophiles are distributed across many phylogenetic groups, comprising aerobic, anaerobic, chemoheterotrophic, photoheterotrophic, and/or photoautotrophic species. Some of the most relevant phyla hosting salt-loving bacteria include Pseudomonadota, Firmicutes, Actinomycetota, Bacteroidota and Cyanobacteria, each one of them with several genera and species identified, showcasing the richness of microbial life in these extreme habitats. Some representative Pseudomonadota able to thrive in brine substrates belong to *Halomonas* and *Salinivibrio* genera (Gorriti et al., 2014; Carlson et al., 2016). For Firmicutes, a classic example is the genus *Halobacillus* (Chen et al., 2009). Regarding the phylum Actinomycetota, species affiliated to *Streptomyces, Micromonospora* or *Salinactinospora* have been described as true inhabitants of such hypersaline conditions (Chang et al., 2012; Villalobos et al., 2021), while in the phylum Bacteroidota the genus *Psychroflexus* includes various representatives that have been isolated from brine samples (Chun et al., 2014). When mentioning the

Table 2
Selected microorganisms for potential cultivation in brine with their biotechnological applications.

Organism and phylum	Genus	Biotechnological applications	Reference
Bacteria: Pseudomonadota	*Halomonas*	Hosts for microbial cell factory engineering	(Ye and Chen, 2021)
		Biopolyesters such as polyhydroxyalkanoates (PHA) and polyhydroxybutyrate (PHB), gaseous hydrocarbon (bio-propane), osmolytes (ectoine) used as a moisturizer for skin care and anti-aging cosmetics	(Benítez-Mateos and Paradisi, 2023; Aytar Celik et al., 2023; Chen et al., 2022; Faulkner et al., 2023)
Bacteria: Pseudomonadota	*Salinivibrio*	PHA and ectoine	(Van Thuoc et al., 2020; Guynn et al., 2023)
		Decolorization and bioremediation of synthetic dyes	(John et al., 2020)
Bacteria: Firmicutes	*Halobacillus*	Carotenoids (antioxidants)	(Köcher et al., 2009)
		Enzymes (industrial applications – detergents)	(Santos et al., 2021)
Bacteria: Actinomycetota	*Streptomyces*	Antimicrobials, enzymes, pigments, cell factory engineering	(Dharmaraj, 2010; Alam et al., 2022; Del Carratore et al., 2022; Liu et al., 2024)
Bacteria: Actinomycetota	*Micromonospora*	Antimicrobials, anticancer compounds	(Boumehira et al., 2016; Abdel-Mageed et al., 2021; Yan et al., 2022)
		Enzymes	(Carro et al., 2018)
Bacteria: Actinomycetota	*Salinactinospora*	Antimicrobials	(Claverías et al., 2015)
Bacteria: Bacteroidota	*Psychroflexus*	Exopolysaccharides, polyunsaturated fatty acids (for thermostability)	(Feng et al., 2014)
Bacteria: Cyanobacteria	*Aphanothece*	Biostimulants	(Fal et al., 2023)
		Energy	(Chinchusak et al., 2023)
Bacteria: Cyanobacteria	*Euhalothece*	Pigments, mycosporine-like amino acids (MAAs) (for biomedicine, cosmetics)	(Mogany et al., 2018; Yang et al., 2020)
Bacteria: Cyanobacteria	*Halothece*	Phenolic compounds, phycobiliproteins and MAAs	(Patipong et al., 2019)
Bacteria: Cyanobacteria	*Phormidium*	Fertilizer supplement	(Koch et al., 2022)
		Nanomedicine, bioremediation	(Asif et al., 2023)
Bacteria: Cyanobacteria	*Halospirulina*	Additives, stabilizers, sweeteners	(Kuroiwa et al., 2014)
Bacteria: Cyanobacteria	*Spirulina*	Protein and pigment (phycocyanin) for medical applications and food colorant	(Sandeep et al., 2013; Jester et al., 2022; Mittal et al., 2024)
		Carbohydrates and lipids for biofuels (bioethanol and biodiesel)	(Mata et al., 2020)
		Biomass as fertilizer or animal feed	(Matos et al., 2021)
Bacteria: Cyanobacteria	*Halomicronema*	Toxic compounds for medical applications	(Mutalipassi et al., 2019)
		Pigments (dyes, colourants, cosmetics)	(Patel et al., 2018)
Fungi: Ascomycota	*Aureobasidium* *Aspergillus*	Enzymes, polysaccharides, biosurfactants (food, energy, materials)	(Wang et al., 2022; Rensink et al., 2024)
Fungi: Ascomycota	*Cladosporium*	Enzymes (wastewater treatment)	(Ben Hmad and Gargouri, 2024)
		Medicine	(Agrawal et al., 2024)
Fungi: Ascomycota	*Penicillium*	Bioremediation	(Bonaventure et al., 2023)
		Biostimulants	(Tarroum et al., 2022)
		Enzymes	(Toghueo and Boyom, 2020)
Microalgae: Chlorophyta	*Chlorella*	Bioremediation, energy, construction, bioplastics	(Almutairi et al., 2021; Al-Hammadi and Güngörmüşler, 2024)
		Cell factory hosts	(Gu et al., 2023)
Microalgae: Chlorophyta	*Scenedesmus*	Lipids (for energy)	(Anand et al., 2019; Calhoun et al., 2021)
		Bioremediation	(Maeng et al., 2018)
Microalgae: Chlorophyta	*Dunaliella*	Lipids, proteins, pigments, glycerol (food, energy, cosmetics, medicine), bioremediation	(Barbosa et al., 2023; Silva et al., 2021; Borowitzka, 2013; Khan et al., 2018)
Microalgae: Gyrista	*Nannochloropsis*	Lipids, cell factory hosts (food, biofuels, oleochemicals)	(ElBarmelgy et al., 2021; Xu, 2022; Canini et al., 2024)
Plants: Amaranthaceae	*Salicornia*	Protein	(Oron et al., 2023; Park et al., 2023)
		Fiber, vitamins, polyphenols	(Fitzner et al., 2021)
		Chlorophylls, carotenoids	(Lyra et al., 2022)
		Food	(Al-Tamimi et al., 2023)
		Animal feed, biofuel	(Fitzner et al., 2021)
		Soil remediation	
Plants: Amaranthaceae	*Atriplex*	Animal feed, soil remediation, erosion control, revegetation, landscaping	(Lucker et al., 2023; Gómez-Bellot et al., 2021; Glenn et al., 2009; Rocha de Moura et al., 2019; Jordan et al., 2009)

photoautotrophic Cyanobacteria, a diverse range of genera was reported to live at high salinities, including *Aphanothece, Euhalothece, Halothece, Phormidium, Halospirulina* and *Halomicronema* (Oren, 2015). In addition, salty environments are a rich source of novel taxa. In fact, representing a distinct niche from other habitats, some novel phyla have been exclusively found in salt-saturated conditions, highlighting the evolution of specialized microbial communities in these environments (Ghai et al., 2011). Either recovered using classic culture approaches, or based on metagenomic insights, examples include the extremely halophilic *Salinibacter ruber*, isolated from saltern crystallizer ponds (Antón et al., 2002), the moderately halophilic bacterium *Spiribacter salinus* retrieved from a saltern (León et al., 2014), or the exceptionally halotolerant *Anianabacter salinae*, isolated from brine of a millennial continental saltern (Azpiazu-Muniozguren et al., 2022).

Halophilic bacteria can thus be cultivated in brine. Moreover, integrated circular cultivation systems of high socio-economic and environmental perspective have been proposed for inland desalination concentrates. An example includes *Spirulina* cultivation, fish *Tilapia* farming, irrigation of halophyte *Atriplex* plant fields, and feeding livestock with the harvested biomass that is of particular interest in rural arid regions (Sánchez et al., 2015). In another study, where a halophilic mixed culture was used for the treatment of industrial residual process brine, up to 100 % removal of $MgCl_2$ was achieved (Mainka et al., 2022).

Examples of biotechnologically relevant activities include anticancer properties that have been recorded from bacterial halophiles isolated from brine-seawater interfaces affiliated to the *Halomonas* and *Sulfitobacter* genera (Sagar et al., 2013), or the discovery of novel enzymes such as proteases, amylases, and lipases that can perform catalytic reactions under harsh biophysical conditions, and are thus greatly useful in industrial processes (Renn et al., 2021). The vast array of potential biological applications of microorganisms that could be cultivated using brine is presented in Table 2.

6.1.2. Fungi

Cultivable fungi in desalination waters, to the best of our knowledge, have not been investigated in great detail. Only certain fungal species, such as representatives of the genera *Fusarium* and the black yeast *Phialophora* were found to colonize cellulose acetate filters from RO desalination processes (Ho et al., 1983). Nevertheless, extremophilic and extremotolerant fungi, also those that were isolated from hypersaline environments, have an interesting potential to be used in several industries (enzymes, antibiotics, Table 2). They have also potential in agriculture as plant-growth promoting microorganisms, but only after balancing their potential dual role both as mitigators of crop diseases and as opportunistic pathogens (Yarzábal Rodríguez et al., 2024). Generally, fungal biodiversity has been based on investigations of biofouling and mixed prokaryotic-eukaryotic microbial biofilms formed in different parts of desalination plants. There, fungal communities were dominated by Ascomycota (98 %), while Basidiomycota made up about 2 %, and the rest were Glomeromycota and unclassified fungi (Ashhab et al., 2014). All Ascomycota belonged to subphylum Pezizomycotina, class Dothideomycetes and family *Capnodiaceae*, while all Basidiomycota belonged to subphylum Agaricomycotina (Belila et al., 2017; Saeed et al., 2019). These results are generally in accordance with the reports on halotolerant and halophilic fungi in natural hypersaline environments worldwide (Gostinčar and Gunde-Cimerman, 2023; Gostinčar et al., 2023). In nature, fungi populate salt flats, salterns, and other high-salt habitats, including those with high concentrations of other salts, such as bitterns, rich with $MgCl_2$ (Zajc et al., 2014) or waters of the Dead Sea (Wasser et al., 2003; Kis-Papo et al., 2003).

Fungi in hypersaline environments can be divided into three main groups. The first is represented by halotolerant sporadic and occasional residents. Their relative abundance varies, emphasizing the influence of surrounding conditions. Adaptations of these fungi ranges from tolerance to low water activity to thriving in salt-free media. Among fungi that represent sporadic occurrences are representatives of the genera *Alternaria, Aspergillus, Mycosphaerella, Penicillium* and *Phoma* (Gunde-Cimerman et al., 2005; Gunde-Cimerman et al., 2009; Gunde-Cimerman and Zalar, 2014). The second, more halo-adapted group, is represented by polyextremotolerant generalistic species, that occur frequently in hypersaline environments, but are adapted to more than one type of stress. Within this group are the biotechnologically important *Aureobasidium pullulans, A. melanogenum* and different species of the genera *Cladosporium, Aspergillus* and *Penicillium* (Table 2). These fungi are generally adapted to salinity from 10–15 % NaCl (Gostinčar and Gunde-Cimerman, 2023; Gostinčar et al., 2022). The third group are core community members, playing pivotal roles in hypersaline ecosystems globally. The dominant fungi within this group are the black yeasts such as *Hortaea werneckii* and the halophilic basidiomycetous genus *Wallemia. H. werneckii* and *W. ichthyophaga* have become model organisms for studying halotolerance and halophily in fungi as they exhibit remarkable adaptations to extreme salinity (Gostinčar and Gunde-Cimerman, 2023; Gunde-Cimerman and Plemenitaš, 2006; Gunde-Cimerman et al., 2018).

6.1.3. Microalgae

Microalgae are photosynthetic autotrophic microorganisms typically inhabiting fresh and saltwater environments and extra-aquatic habitats, found in water column, on submerged or moistened surfaces, in sediments or soil. They occur singly, or can form coenobia or chains of diverse morphology. Their rapid propagation, hight photosynthetic efficiency and the ability to accumulate large amounts of valuable bioproducts make microalgae a suitable biosynthetic platform for industrial raw materials for food, biofuels and other high-value compounds. In addition, microalgal cultivation in brine can have positive environmental impacts. Photosynthetic microorganisms naturally remove CO_2 by fixation, thus reducing its emissions. For instance, as CO_2 is considered as a contaminant in biogas production, it can be coupled with algal cultivation (Rodero et al., 2020). Algae also demonstrate significant potential for removing both organic pollutants (Baghour et al., 2019) and inorganic contaminants (Ordóñez et al., 2023) from water through various mechanisms, including oxidation and biosorption. Overall, there is an increasing interest in the cultivation of microalgae (Tan et al., 2020; Guieysse and Plouviez, 2024).

Species that can be cultivated in desalination brine are, among others, *Chlorella vulgaris, Scenedesmus quadricauda, Nannochloropsis* sp. and *Dunaliella tertiolecta*. They can be used to biodegrade and remove nutrients from polluted water, for example *S. quadricauda*, which has been shown to induce the degradation of polymeric organic matter in the RO concentrate (Maeng et al., 2018). Other species can be cultivated for their biomass and bioactive compounds (Table 2). In fact, some species showed improved biomass production when cultivated in desalination concentrate media compared to other conventional media (ElBarmelgy et al., 2021; Shirazi et al., 2018). An option is also to supplement the commercial growth media with brine to reduce the costs related to growth media, while at the same time valorizing brine. Supplementing commercial media with brine was also shown as beneficial for biomass productivity and bioactive compounds production (Matos et al., 2018; Bhandari and Prajapati, 2022).

6.2. Brine as a medium for supporting the growth of macroorganisms

The use of reject brine for agricultural purposes, including the irrigation of forage shrubs or halophytic crops, as well as its applications as a mineral source for crops in hydroponic systems and aquaculture, is gaining popularity as an alternative approach of managing this waste (Jiménez-Arias et al., 2022).

6.2.1. Soil irrigation for halophytic crops

Halophytes are a relatively small group of taxonomically diverse plants that grow in high-salinity environments where the salt concentration is above 200 mM NaCl (with some species thriving in environments with over 2 M of NaCl (Volkov, 2015)), which is significantly higher than the salinity levels tolerated by most plants (Vu et al., 2022). Halophytes sequester salts, and the degree of salt uptake varies between plant species, affecting the efficiency of their use for remediation of affected soils (Ahmadi et al., 2022). Hence, halophyte cultivation can generate economic yields for rural communities while supporting the ecosystem restoration, reducing the discharge of saline water into sewer systems and natural drainages, and reducing the cost burden of brine disposal from desalination processes, thus allowing for revegetation and phytoremediation of brine-impacted lands (Park et al., 2023; Lucker et al., 2023; Green et al., 2020; Young et al., 2011; Gerhart et al., 2006). In addition to their use in remediation, halophytes have several productive applications (due to their high levels of protein, phenolic compounds, lipids, and essential minerals like potassium, calcium, and magnesium): production of food, oilseeds for human consumption and biodiesel, and animal feed, among others (Panta et al., 2014; Centofanti and Bañuelos, 2019; Accogli et al., 2023). For these reasons, halophytes have been identified as promising candidates for cultivation using saline wastewater (Panta et al., 2016). So far, financial analyses of these activities suggest a significant potential for integrating halophytic components into farms utilizing reject brine from desalination plants (Robertson et al., 2019). However, it is important to note that salinity levels may gradually rise due to inadequate drainage systems, which could ultimately lead to soil degradation over time (Al-Faifi et al., 2010).

Desalination brine for irrigation of halophyte crops in biosaline agriculture has already been showcased. Most of the species of halophytes tested belonged to the two genera of Amaranthaceae s.l., *Salicornia* and *Atriplex* (Table 2). *Salicornia* (commonly known as glasswort) attracted much interest because of its crunchy and salty taste, and high nutritional value resulting from approximately 34 % of protein per dry weight and represents an additional local food production resource (e.g., as a highly valued salad vegetable in the Mediterranean diet), coupled with environmental control over brine deposition (Oron et al., 2023; Lyra et al., 2022; Lee et al., 2024). In regions such as Northern France and The Netherlands, *Salicornia* is already featured in local dishes and culinary publications. While market prices vary, *Salicornia* species have been sold in niche markets at rates of up $8 per kilogram. Their culinary versatility extends to products such as burgers, crackers, and juices (Lee et al., 2024; Bazihizina et al., 2024). Moreover, there is growing interest in *S. bigelovii* due to its potential in the production of edible oils and biofuels as its seeds contain over 25 % of oil (Al-Tamimi et al., 2023). When irrigated with nutrition-rich brine from aquaculture systems, *S. bigelovii* demonstrated yields up to 16 kg/m^2. The gross economic water productivity (GEWP) of such systems ranges from $1.5 to $6.2 per kilogram, exceeding desalination costs by up to fourfold (Al-Tamimi et al., 2023). Financial analyses estimate that under optimal conditions, cultivation of *S. bigelovii* can yield returns of approximately $76,000 per hectare, outperforming other halophytes like *Distichlis spicata*, and *Sporobolus virginicus*.

The other popular genus in the experimental brine-irrigated biosaline agriculture is *Atriplex*, appreciated for its value as animal feed, as well as in phytoremediation, erosion control, revegetation, landscape projects, and supporting wildlife habitats (Lucker et al., 2023; Gómez-Bellot et al., 2021; Glenn et al., 2009; Rocha de Moura et al., 2019; Jordan et al., 2009). It is primarily cultivated as forage in (semi) arid regions, including parts of Brazil and Australia. Known for its exceptional resilience to salinity and drought, *Atriplex* is especially valuable for livestock production in harsh environments. Its capacity to maintain high biomass yields under extreme conditions makes it an important asset for sustainable agriculture in saline and arid zones (Porto et al., 2006).

As it was already noted, integrated agricultural systems are highly prospective in respect to brine pretreatment before plant irrigation. In these systems, desalination brine is first used as the medium for land-based hypersaline aquaculture (first for growing duckweed or *Spirulina*, then for growing fish), where it becomes enriched with nitrogen and phosphorus from fish waste (Sánchez et al., 2015; Oron et al., 2023). The integrated approach maximizes the use of brine for food production and environmental control. Such nutrient-enriched »aquabrine« has a more positive impact on the irrigated plants than the crude desalination brine (Al-Tamimi et al., 2023).

6.2.2. *Hydroponic farming*

Hydroponics is a method for growing agricultural crops without soil using a water-enriched nutrient solution. This method may also include an aggregate substrate such as vermiculite, coconut coir or perlite (Khan, 2018). Hydroponic systems are very efficient in terms of nutrient and water use, as well as crop yield. A wide range of commercial crops can be grown hydroponically, such as tomatoes, cucumbers, lettuce and strawberries (Kannan et al., 2022).

Rejected brine from desalination plants can be potentially used as a water and nutrient source in hydroponic systems, providing a suitable nutrient composition. For example, the rejected brine from a desalination plant in Tenerife (Canary Islands), diluted 1:40 and enriched with Hoagland's standard nutrient solution, was tested as hydroponic medium for tomatoes. Although the yield of fruits reduced in fresh weight by 40 % compared to control plants, the organoleptic properties of the fruits improved, as deduced from their total soluble solids, dry matter percentage, titrable acidity and pH. These results were attributed to a high content of macronutrient ions in brine, especially Ca^{2+}, K^{+}, Mg^{2+}, while the Na^{+} content reached levels above 16 $g\ L^{-1}$, adding to overall brine salinity and conductivity (Jiménez-Arias et al., 2020). Later, a one-year study of the rejected brine from 5 desalination plants in Tenerife showed that specific minerals were found at consistently reliable high concentrations during analyses (Ca^{2+}, K^{+}, Mg^{2+}, SO_4^{2-} and B^{-}), regardless of the plant location, and the rejected brine can successfully be used to hydroponically cultivate carnations (Jiménez-Arias et al., 2022). The studies in Tenerife suggest that implementing a hydroponic system adjacent to hotel desalination plants could enable the production of horticultural and floricultural crops. From the economic point of view, the use of rejected brine at a dilution of 1/40 directly saves 20 % of hydroponic solution cost due to the mineral nutrients present in the brine (Jiménez-Arias et al., 2020). Also, the use of rejected brine from desalination plants may reduce the fertilization cost by 21 % without productivity losses (Jiménez-Arias et al., 2022; Magán et al., 2008).

In Brazil, hydroponic experiments were conducted with a variety of mini-watermelon and rejected brine from desalination plants. Growth, physiological responses, yield and fruit quality of mini-watermelons were evaluated. For these experiments, plants were grown in hydroponic systems with mixtures of brine and tap water at three different proportions ranging from 15 %–60 % brine and different substrates. The use of saline solution in water mixtures up to 6.90 dS m^{-1} (60 % saline solution) in the preparation of hydroponic nutrient solutions reduced the growth of the fruits, but did not affect their chemical properties. In fact, there was an improvement in the vitamin C and soluble solids content of the fruit of plants grown with the brine. An increase in soluble solids content of the fruit is related to the amount of sugars and therefore to the taste of the fruit, giving a higher quality product. From the photosynthetic responses of the mini-watermelon subjected to salt stress, authors deduced that reductions in plant growth are not related to low photosynthetic efficiency, but rather to the reduction of photosynthetically active leaf area, due to disturbances in cell growth and expansion (Da Silva et al., 2022). In subsequent studies, it was found that although salt stress affected fruit production in mini-watermelon, it was not detrimental to seed production, viability and seed vigor (Alves et al., 2022).

6.2.3. *Aquaculture*

Brine can effectively be used for fish farming of tilapia, which is the common name for nearly one hundred species of cichlid fish. Tilapia are mostly freshwater fish found in shallow streams, ponds, rivers and lakes. Red tilapia are tolerant to salt water (Mirera and Okemwa, 2023).

Several countries have introduced red tilapia farming and over the last 20 years, indeed, saltwater tilapia farming has increased exponentially from 1.6 thousand tonnes live weight in 2000 to 107.4 thousand tonnes in 2020 (FAO 2022).

In Brazil, the "Agua Doce" programme takes a different approach to the disposal of brine rejects from small and medium-sized inland desalination plants to serve rural communities or to augment fresh water supplies. The valorization of the rejected brine starts with its use in fish farming of tilapia species, which are well adapted to high salinity. In a second step, the brine leaving the tilapia ponds is mixed with organic fertilizers (manure from local livestock) and used to irrigate halophyte fodder for local livestock. Since this solution was adopted, several villages in the semi-arid regions of Brazil have benefited from both a potable water supply and a boost to the local economy (Sánchez et al., 2015). The socio-economic analysis of this programme showed that, although it may not be profitable in the short term to recoup the initial investment (15 years would be required for a return on the invested capital), positive social and environmental impacts were generated by adding value to the rejected brine and providing food and nutritional security for family farming (Souza et al., 2022).

Brine can also be used for growing Artemia, an essential live feed for the aquaculture industry (K. Madkour et al., 2023). Artemia, commonly known as brine shrimp, is a crustacean that can tolerate high levels of salt. This makes it a suitable candidate for cultivation in desalination effluents, especially when integrated with algal cultivation and fish aquaculture in multitrophic systems (Sánchez and Matos, 2018). Despite its potential, further research is needed to optimize the growth conditions for Artemia cultivation in desalination brine.

Compared to halophyte agriculture, the use of brine from desalination plants can have a wide application potential in aquaculture, both for fish and microalgae, with lower risks as increased salt concentrations do not affect the soil/arable land. However, the bioaccumulation of toxic substances that may occur in the aquaculture of certain organisms when using rejected brine must be assessed on a case-by-case basis.

6.3. Biodesalination processes

Besides cultivation in brine, innovative approaches can also consider biological desalination (biodesalination). Estimates for brackish water desalination suggest a potential efficiency of 40 % salt removal of biodesalination by algae and cyanobacteria (A.M. Zafar et al., 2022). Salt removal efficiency depends on the temperature (Wei et al., 2020). It is an inventive approach to desalination, functioning through the assimilation and retention of salts by various salt-tolerant living organisms. In addition, economically important secondary metabolites can be produced by organisms that can survive at high salt concentrations. In a win-win strategy, the resulting biomass from biodesalination can be used in biotechnological applications.

6.3.1. Use of microalgae for desalination processes

In search of environmentally friendly desalination processes, algal-based desalination is of potential relevance through mechanisms of biosorption (through adsorption) and bioaccumulation (through absorption) (Wei et al., 2020; L. Gao et al., 2021; Kumar Patel et al., 2021). An additional added benefit is to couple biodesalination with halophilic strains capable of biodegradation of aromatic compounds and other contaminants in brine, parallel to what has been suggested for treatment of saline wastewater, generated by several industries, such as petroleum, tannery and textile ones (Mainka et al., 2021). The reduction of carbon emissions from algal photosynthesis is an additional benefit of biodesalination.

Microalgae of the genera *Dunaliella, Scenedesmus* and *Chlorella* have all been used for biodesalination purposes with up to 67 % of desalination success (Shirazi et al., 2018; Kumar Patel et al., 2021; Sahle-Demessie et al., 2019; Moayedi et al., 2019; Barahoei et al., 2021). Species of cyanobacterial genera such as *Phormidium, Synechococcus* and *Synechocystis* have also shown potential for use in biodesalination processes (Amezaga et al., 2014; Minas et al., 2015; A.M. Zafar et al., 2022). Genetic engineering techniques and co-culturing have also been used to increase both salt tolerance and desalination efficiency of the algae (Danaeifar et al., 2023).

Despite its potential as a sustainable technology, algal-based desalination is still in its early stages of development. The limitations of such systems are their overall higher cost due to the extended contact time required for the slow bioaccumulation processes, a lower capability of salt removal compared to the existing desalination alternatives, inhibition of algal growth by high salinity, and high costs associated with separating algal biomass from the medium, the dependency on temperature, light conditions, pH, and nutrients (L. Gao et al., 2021; Sergany et al., 2019). Realistically, such technologies can serve as auxiliary desalination units in hybrid desalination setups or the first step of partial desalination, functioning as a pre-treatment desalination stage (L. Gao et al., 2021; L. Gao et al., 2021) and preparing microalgae for use while the partially desalinated brine is applied in other technologies (e.g., cultivation of biotechnologically relevant microorganisms, as proposed above, and also in Table 2). Further research, technological improvements, feasibility studies, and life cycle analyses are essential to advance desalination technology beyond the proof-of-concept stage.

6.3.2. Growth/cultivation of seaweed near desalination plants

The role of seaweed in achieving a circular economy has gained significant attention in recent years (Torres et al., 2019). The term seaweed refers to macroalgae typically originating from the marine environment but may also be extended to species of freshwater macroalgae. Seaweeds are a renewable resource, used as a source of food, feed, or for a wide range of commercial products. Considering also their rapid growth rate coupled with a low environmental impact and their ability to sequester carbon, seaweeds are ideal candidates for circular economy (Yong et al., 2022).

Seaweed can absorb and assimilate nutrients or waste and effectively reduce their concentration from brine discharge and, in turn, produce valuable seaweed biomass. They essentially act as natural biofilters. As a result, the brine released back into the environment after phycoremediation with seaweed will have reduced nutrient levels, reducing its impact on marine ecosystems health. Seaweed are widely used for bioremediation as part of integrated multitrophic aquaculture (IMTA) systems (Chopin and Tacon, 2021). This logic can therefore be extended to bioremediation of other industrial processes such as desalination.

The selection of species, however, is critical as not all species are adapted to high salinity or are amenable to land-based aquaculture. Another major problem when selecting species for a circular economy approach is the need to identify candidates with an existing market demand. *Gracilaria, Pyropia* (nori) and *Ulva* (sea lettuce) are three examples of seaweeds that are well-adapted to thrive in high salinity environments such as those created by brine discharge. The candidates mentioned above are currently utilized for a range of commercial applications and are linked to an established market (Araújo et al., 2021). For example, *Gracilaria* is used for the extraction of hydrocolloids, while *Pyropia* and *Ulva* are applied for food and feed respectively. Research using *Ulva* for bioremediation already exists (Yokoyama and Ishihi, 2010) and can provide a foundation for its application in desalination, a field in which seaweed has not yet been sufficiently studied or implemented. The principles of phycoremediation may be applied to seaweed for bioremediation as well as for the accumulation of heavy metals (Ali et al., 2013).

Phycoremediation using seaweed could indeed become integrated into the design of desalination plants. Constructing raceways or ponds near brine discharge outflow would enable the seaweed to naturally absorb nutrients over a short period of time. This integration not only supports environmental stewardship but also aligns with the principles of circular economy by transforming waste into a valuable resource (Araújo et al., 2021). The concept of integrating seaweed as natural biofilters in desalination plants has not been extensively explored in the literature, yet it holds significant potential. However, further research and development is required, particularly in selecting species or strains (Lawton et al., 2013), with an emphasis on local or endemic varieties.

Further research into cultivation conditions, nutrient uptake rates (Roleda and Hurd, 2019), and biomass harvesting methods or stocking densities is also needed to ensure the effectiveness of the treatment. Finally, collaboration between industry, i.e., desalination plants, researchers, and environmental agencies will be crucial (Sola et al., 2020). Regulatory frameworks and guidelines should also be established to ensure that the treated brine meets acceptable environmental standards before being discharged into the marine environment and that the phycoremediation process using seaweed is indeed effective. With this in mind, safety standards should also be applied to the seaweed biomass to ensure that it is safe for commercial applications (Banach et al., 2020).

7. Technical, economic and social perspective

Several of the solutions presented in the previous chapter already show the market potential for targeted cultivation of organisms (Table 3). Regarding bacteria, recent case studies with halophilic and halotolerant microorganisms have demonstrated that saline environments can support both high-margin and bulk bioprocesses. Ectoine, a compatible solute valued at almost 1000 USD per kilogram and with increasing demand (Cantera et al., 2020), has a production of over 15, 000 tons per year (Hobmeier et al., 2022). The production is based on bacterial milking, which includes microbial growth in high salinity media (15 % (w/v) NaCl for *Halomonas elongata*) (Kunte et al., 2014). A techno-economic analysis of ectoine production using *Methylomicrobium alcaliphilum* in bubble-column reactors fed with methane estimated production costs of 158 - 275 € per kg, substantially lower than the market price range of 600 - 1000 € per kg. These cost savings were largely attributed to the high salinity enabling non-sterile operation and the use of low-cost carbon sources such as methane (Pérez et al., 2021). In a separate study, a 7.5 L non-sterile seawater fermentation with engineered *Vibrio natriegens* produced 41 $g\,L^{-1}$ of 2,3-butanediol with a productivity of 3.4 $g\,L^{-1}\,h^{-1}$, illustrating that salinity can replace steam sterilisation while still delivering competitive titres and productivities (Meng et al., 2022). However, as processes are scaled up, the benefits of high-salinity media must be weighed against several technical limitations. Equipment corrosion, increased energy demands for pumping viscous or dense brines, and material compatibility become significant cost drivers. More critically, scale-up introduces oxygen transfer bottlenecks: as NaCl concentrations rise, salt precipitation may occur and the volumetric oxygen-transfer coefficient (kLa) drops significantly, impairing aerobic metabolism. Overcoming these issues may require customised reactor designs to maintain efficient gas-liquid mass transfer. Generally, desalination brines offer a promising, cost-effective culture medium for halophilic and halotolerant microorganisms, supporting the sustainable production of high-value biochemicals such as ectoine and biosurfactants (Oren, 2010). Their naturally high salinity reduces contamination risks and selectively promotes the growth of target strains. Still, their ionic imbalance and potential toxicity may inhibit growth unless pre-treatment and nutrient supplementation are applied (Backer et al., 2022). Furthermore, downstream processing in salt-rich matrices remains a critical hurdle, as it is often energy-intensive and technically complex.

The global market value of algal production is approaching a billion USD (Table 3 shows the segment for pigments) (Yildirim et al., 2022). Among microalgae that can be cultivated in brine, *Dunaliella salina* currently holds the strongest commercial position (Meticulous research 2024; Global Market Insights 2023). The projected market growth (Table 3) is primarily driven by demand for natural β-carotene in the nutraceutical, cosmetics, aquaculture, and animal feed sectors. With the productivity of 15 g of β-carotene per 1 ton of growth medium, the daily world production of 50 million m^3 of brine could support the production of 750 tons of β-carotene per day (Yildirim et al., 2022). Increasing consumer preference for natural products over synthetic alternatives supports this trend, despite regulatory and production scale up complexities (Prates, 2025). However, microalgae cultivation in brine, especially hypersaline brines such as RO concentrate, often requires dilution or pretreatment to reduce salinity and remove inhibitory components (Rawat et al., 2011). Techno-economically, open raceway ponds offer lower capital costs but higher water consumption and land use, whereas photobioreactors enable controlled environments with higher productivity but incur significantly higher energy inputs and operational costs (Barsanti and Gualtieri, 2014; Slade and Bauen, 2013). Life Cycle Assessment (LCA) studies show that environmental impacts of algae systems significantly differ, depending on the cultivation method, with photobioreactors consuming 5–10 times more energy per unit biomass than open ponds but offering improved land-use efficiency and product purity (Clarens et al., 2010; Lardon et al., 2009).

Despite lower yields compared to conventional crops, halophytes are gaining traction across sectors due to their resilience and ability to grow in saline conditions. The halophyte-based biodiesel market (Table 3) is driven by demand for renewable, non-food-based fuels and tightening environmental regulations (Verified Market Reports 2025). The saline agriculture market is expected to double by 2033, especially in regions facing salinity or freshwater scarcity (Bussiness Research Insights 2024). The estimated gross returns range between $1500–$5000 per hectare annually, depending on the product and market access (Panta et al., 2014). Halophyte cultivation enables the use of marginal lands, relieving pressure on fertile soils and freshwater. However, the sector still faces infrastructure challenges, underdeveloped food markets, and ecological risks such as the spread of invasive species (Al Hassan et al., 2016). Moreover, scalability is restricted by land requirements, species-specific salt tolerances, and risks of soil salinization. The global Artemia market is driven by growing demand for sustainable live feed in aquaculture. However, natural Artemia populations are highly vulnerable to habitat loss, pollution, and climate change, with over half of cyst-producing salt lakes facing degradation. Reliance on wild harvesting raises ecological concerns and threatens supply stability (K. Madkour et al., 2023; Zion Market Research 2024). In this context, controlled Artemia cultivation using desalination brine offers a promising alternative that supports both resource sustainability and aquaculture resilience.

In terms of social sustainability, social LCA (S-LCA) is still immature

Table 3
Selected organisms with potential for cultivation in brine, along with their applications and market value. CAGR (Compound Annual Growth Rate).

Organism	Application	Market value	Reference
Bacteria	Industrial enzymes	$5.9 billion in 2020 and projected to grow at a CAGR of 7.6 % from 2021 to 2026	(Rathakrishnan and Gopalan, 2022; Enache and Kamekura, 2010)
Microalgae	Pigments	$51–88 million in 2022/2023 and projected to grow at a CAGR of up to 4.4 % until 2032	(Meticulous research 2024; Global Market Insights 2023)
Plants	Biodiesel	$1.2 billion in 2024, growing at a CAGR of 15.2 %	(Verified Market Reports 2025)
Plants	Agriculture	$1.63 billion in 2024, with a CAGR of 8.5 %	(Bussiness Research Insights 2024)
Artemia	Feed	$144 million in 2022 and projected to grow at a CAGR of 9.38 % between 2023 and 2030	(Zion Market Research 2024)

compared to LCA (Harris et al., 2025; Iofrida et al., 2018), and most work using life cycle methods to assess, e.g., wastewater management systems, is limited to only one or two of the sustainability pillars and omits that of social sustainability (Tsalidis et al., 2023). The situation is similar in the brine industry: while the technical, environmental and economic aspects of brine treatment systems are found in the literature, the social performance of the industry and brine treatment systems is not clearly introduced (Tsalidis et al., 2020). The aim of S-LCA is to assess the social risks and opportunities of brine valorization and to understand how brine impacts people – starting with workers and local communities who may be most affected, as well as potential customers and all other stakeholders. As far as workers are concerned, the most important aspects are working conditions, the impact of brine reuse on health, environmental safety, water valuation and land use. Potential customers could gain access to more affordable materials/products, which has a positive impact on their social life (Tsalidis et al., 2020). While The S-LCA does not provide information on whether or not a product should be manufactured, the information gained from an S-LCA can nevertheless provide “food for thought” and be helpful in decision-making (Life Cycle Initiative).

Desalination brine offers a viable and sustainable alternative to conventional culture media, and does not demand the use of arable land (in case of halophytes), thus representing promising avenues for resource recovery and economic gain, supporting a circular bioeconomy framework. The potential for valorizing brine depends on species selection, regional market demands, brine composition, technological advancements, supportive policies and acceptance. Scale-up challenges, particularly the effects of high salinity on reactor design and downstream processing, must be addressed to ensure technical feasibility. Additionally, market competition and regulatory approvals can pose significant barriers to commercialization (Oren, 2010).

8. Conclusions

- Halophilic organisms, originating from different taxonomic groups, possess unique physiological and biochemical characteristics that make them ideal for biotechnological applications. Desalination brine, a by-product of desalination processes, can be used as a valuable medium for cultivating these organisms. This approach offers a more circular and sustainable alternative to brine disposal, which can otherwise be harmful to the environment.
- Desalination brines are most commonly studied for algal cultivation and growth. Algae can be used for prodution of valuable metabolites and biomass. Furthermore, algae can also be utilized to purify polluted brines, offering an environmentally friendly solution. However, other organisms are of high potential and future efforts should concentrate on optimizing the cultivation conditions for (i) algae and (ii) other organisms of biotechnological relevance.
- Another high-potential innovative solution that reduces the quantities of discharged brine are integrated desalination approaches, where processes of (bio)desalination are coupled with the cultivation of biotechnologically relevant (micro)organisms. These can be utilized in industries such as food, feed, agriculture, and biomedicine. However, brine components and residual contaminants can be hazardous when spread over large agricultural areas. This approach therefore has to be carefully managed and monitored to safeguard the environment, ensure the safety of agricultural products and protect human health.
- Overall, further research is needed to identify the most promising strains for industrial applications and optimize and scale up the biodesalination as well as to use brine in agriculture, aquaculture and biotechnology. The most promising crops, species and strains for industrial applications should be identified.
- Nevertheless, it is essential to embrace innovative solutions that are not only effective but also sustainable. This research should hence involve tailoring approaches to specific local conditions, including assessment of environmental impact, environmental sustainability, techno-economic viability and social implications.

CRediT authorship contribution statement

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Supplementary materials

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Data availability

No data was used for the research described in the article

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