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Microalgal-based desalination brine remediation: Achievements, challenges, and future research trends

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A R T I C L E I N F O

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A B S T R A C T

Desalination brine discharge has several negative impacts on the marine environment, such as increase in salinity levels, effects on marine biodiversity, and alteration of the physical and chemical characteristics of water. In addition, desalination plants consume significant amounts of energy, which contribute to carbon emissions and global warming. Various brine management strategies have been adopted to mitigate the negative impacts of brine discharge, these are often expensive, require extensive infrastructure, and may not be feasible in all locations. The focus of this review is Algae-based brine bioremediation, which is a promising approach to managing brine discharge, as it not only reduces the environmental pollution impacts of brine discharge but also produces valuable biomass products. Mechanisms employed by microalgae for brine bioremediation, including nutrient recovery, organic and heavy metal removal through processes like biosorption, bioaccumulation, and metal detoxification are discussed. Algae can grow in high salinity water and use the nutrients present in brine to produce biomass, which can be harvested and used for a variety of applications, including biofuels, feed, and pharmaceuticals. This approach can potentially provide a sustainable and cost-effective solution to managing brine discharge from desalination plants. The review highlights achievements in microalgae-based brine remediation, including nutrient sequestration and the valorization of microalgal biomass after treatment. Challenges in this field, including brine's high salinity and algal biomass harvesting, are addressed. The paper also outlines research trends that encompass strain selection and optimization, carbon capture, nutrient recycling, photobioreactor design, anaerobic digestion, biochar production, and techno-economic feasibility analysis. These future-focused approaches aim to enhance the sustainability and efficacy of microalgal biomass cultivation in brine remediation.

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Nomenclature/Abbreviation

RO	Reverse osmosis
DOP	Dissolved organic phosphorus
TOP	Total organic phosphorus
ZLD	Zero liquid discharge
MSF	Multi-Stage Flash
DO	Dissolved Oxygen
SWRO	Seawater reverse osmosis
BCD	Bacterial carbon demand
MD	Membrane Distillation
ED	Electrodialysis
CEM	Cation exchange membrane
AEM	Anion exchange membrane
DC	Desalination concentrate
RWP	Raceway Pond
ROS	Reactive oxygen species
HEDP	Hydroxyethylidene diphosphonic acid
DTPMP	diethylenetriamine penta methylene phosphonic acid
GHG	Greenhouse gases
MPBR	Membrane photobioreactor
HRT	Hydraulic retention time
SRT	Solid retention time
PBR	Photobioreactor

1. Introduction

Due to the growing global demands, freshwater resources are depleted increasingly making it difficult to access clean and safe water. Rapid industrialization as well as climate change in populated areas moreover contribute significantly to increasing water demand (Matos et al., 2024). By 2050, it is estimated that the global population will increase by 10 billion. Additionally, projections suggest that around 75% of the world's population will likely experience water shortages by that time (Panagopoulos et al., 2019). To address this problem, many countries regard desalination techniques as an effective means of obtaining fresh water. Consequently, countries of the Middle East and North Africa (MENA) account for about 48% of all seawater desalination undertaking on global scale (Jones et al., 2019).

Brine generated by desalination facilities is commonly disposed of through various methods, including surface water discharge, deep well injection, sewage discharge, evaporation ponds, and land applications. The optimal strategy for brine disposal is influenced by factors such as the quality, content, and quantity of the brine, geographical location at the discharge point, the appropriateness of the chosen method, and the availability of a suitable disposal site. The surface water discharge approach is the most prevalent, with over 90% of seawater desalination facilities adopting this method to release brine into open water bodies, primarily due to the proximity of desalination plants to the sea (Omerspahic et al., 2022. There are two primary types of brine discharge into open water bodies: surface discharge and sub-surface discharge. Onshore surface discharge of brines, achieved by blending them with cooling water from power plants to decrease salinity, or through sub-surface diffusers, enabling the discharge of brine to extend deeper and farther into the mixing zone of the receiving water body, typically results in a salinity reduction of approximately 10% above the ambient water levels (Kress, 2019). Recent studies indicate limited impacts on water column chemistry when using diffusers for brine disposal (Kress et al., 2020). Additionally, there is a potential risk of harm to benthic environments due to the formation of gravity plumes that traverse bathymetric gradients (Wood et al., 2020). The presence of pollutants not naturally found in the receiving water body, including dangerous pretreatment chemicals, utilized in the desalination process, such as coagulants, antiscalants, and neutralized acids (Kress et al., 2020), may pose potential harm to the marine environment (Katal et al., 2020).

Microalgae culture offers an affordable and green approach coupled with the production of high-value biomass positioning them as a favorable technique for sustainable management of desalination discharge (Zhu et al., 2018; ElBarmelgy et al., 2021; Mehdipour et al., 2023, Deamici et al., 2024). These microbes could assimilate various nutrients, metal contaminants, and organic toxicants from the brines, thereby mitigating the impact (Shirazi et al., 2018). The biomass produced during the process could hold added value and can be harvested for versatile purposes. Various valuable compounds for instance lipids, carbohydrates, proteins, natural pigments, and antioxidants, can be extracted from the processed biomass (Mata et al., 2020). These compounds have a great potential for different industrial applications including food and feed, cosmetics, and pharmaceuticals. Furthermore, the biomass generated post-treatment is considered renewable and sustainable feedstock for biofuel production like biodiesel, bio-hydrogen, and bioethanol (Matos et al., 2024). As a result, the utilization of microalgae to treat desalination brine holds the potential to become a significant, and cost-effective solution to sustainable management of brine (Al Bazedi et al., 2023). Limited research exists on the cultivation of microalgae in desalination brine, highlighting a notable gap in our understanding of its potential applications. Further exploration is necessitated to clarify the prospects of this approach. Particularly, there is scarcity of studies focusing on the scalability and practical implementation of this method, with most of the existing research confined to laboratory-scale investigations. Therefore, there is a need for comprehensive research actions aimed at bridging this gap and uncovering the broader implications and feasibility of utilizing desalination brine for microalgae cultivation on a larger scale. Table 1 provides a rapid assessment of existing review papers that focusses on simultaneous objectives of utilizing brine as a medium to obtain high value microalgal biomass and remediating brine.

This article provides a comprehensive overview of microalgae-based treatment as a promising approach to address brine management challenges. It covers: (i) the chemical composition of brine and its potential ecological repercussions, emphasizing the need for effective remediation strategies; (ii) current brine management practices, paving the way for the introduction of microalgae-based bioremediation; (iii) a discussion on the mechanisms employed by microalgae to tackle brine remediation, encompassing nutrient recovery, organic compound removal, and heavy metal extraction. Various pathways, including biosorption, bioaccumulation, and metal detoxification, are examined in detail; (iv) exploration of microalgae cultivation systems optimized for brine treatment with an emphasis on substantial accomplishments in microalgae-based brine remediation, showcasing the efficient sequestration of nutrients by microalgae from brines; and (v) investigation of the valorization potential of microalgae biomass following brine treatment, covering protein, lipid, carbohydrate, and beta-carotene content. Despite these advancements, challenges such as brine salinity and algal biomass harvesting remain to be investigated.

2. Desalination Brine remediation

2.1. Chemical composition of brine

Brine discharged from desalination plants often contains elevated levels of salts and chemicals for instance phosphate-based antiscalant or sulfate-based aggregating agents. (Frank et al., 2017). Antiscalants are consistently introduced into the Reverse Osmosis (RO) influent, with concentrations typically ranging from 1 to 15 mg/L. However, it is necessary to escalate the dosage by fivefold when aiming for an RO recovery rate exceeding 80% (Wang et al., 2020). Phosphonate exposure is generally deemed non-hazardous to most aquatic organisms, up to a concentration of 100 mg/L (Wang et al., 2020). In a study Kress et al. (2020), deep diffusers, have been used to reduce the effect of both high salinity and the associated nutrients, mainly Phosphorus in the form of diffused organic Phosphorus (DOP), resulting from the use of antiscalants. In situ, studies show that the disposal of brine by deep diffusers resulted in minor effects on water chemistry and biology, including trace elements such as Iron (Kress et al., 2020). Some research emphasizes the potential role of phosphonates in contributing to eutrophication because of their phosphorus-containing structure (Huang et al., 2019; Xu et al., 2019), the interaction between phosphonates and microalgae, pivotal in initiating harmful algal blooms, remains poorly understood (Wang et al., 2020). In another study by Sharifinia et al. (2023), 288 sediment samples were collected from 24 locations near desalination plant outlets in Iran. In addition to high levels of ions like sodium and chloride, calcium and magnesium, and sulfate could be found in significant amounts (Table 1). Other studies suggest the presence of heavy metals

Table 1
Review papers addressing cultivation of microalgae on desalination brine.

No	Title of review	Major outcomes	References
1	The use of desalination concentrate as a potential substrate for microalgae cultivation in Brazil	This review presents instances of microalgae cultivation in desalination concentrate, offering a comprehensive assessment of the impact of desalination concentrate on various parameters such as algal biomass productivity, lipid content, lipid productivity, protein composition, and fatty acids composition.	Matos et al., 2017
2	Desalination concentrate microalgae cultivation: biomass production and applications	This paper undertakes a comprehensive review of the influence of desalination concentrate on microalgal productivity, elucidating instances of microalgae cultivation within desalination concentrate environments. Through an analysis of research findings, it was determined that *Chlorella vulgaris, Scenedesmus quadricauda, Spirulina platensis, Nannochloropsis oculata*, and *Dunaliella tertiolecta* exhibit cultivability within desalination brine settings.	Al Bazedi et al., 2023
3	Influence of desalination concentrate medium on microalgal metabolism, biomass production and biochemical composition	This review aims to encapsulate the intricate response mechanisms exhibited by microalgae when subjected to brine rich environments. Numerous laboratory-based studies have scrutinized the impact of varying DC concentrations on the biochemical composition of microalgae, conducted both in photobioreactors and raceway ponds.	Matos et al., 2024
4	Microalgal-based Desalination Brine Remediation: Achievements, challenges, and future research trends	This article comprehensively explores microalgae-based approaches for brine management, addressing chemical composition, ecological implications, and current practices. It focusses into microalgae mechanisms for brine remediation, including nutrient recovery and heavy metal extraction through biosorption and bioaccumulation. Optimized cultivation systems and achievements in microalgae-based brine remediation are highlighted. The study also investigates the valorization potential of microalgae biomass, encompassing protein, lipid, carbohydrate, and beta-carotene content. The article also addresses challenges and outlines future research trends in the field	Current study

contaminants like Copper, Iron, Nickel, Chromium, and molybdenum in trace amount (Omerspahic et al., 2022). The analysis revealed higher concentrations of heavy metals, particularly copper and lead, in sediments close to the discharge points, indicating local contamination. Hierarchical cluster analysis confirmed the separation of stations impacted by desalination plant discharges from those further away. Despite the elevated metal concentrations, the Pollution Load Index (PLI) values for all sampling stations were below 1, indicating no significant metal pollution according to this index. The Potential Ecological Risk Index (PERI) values suggested a "low potential ecological risk" in the sampled sediments. However, the findings underscore the increase in heavy metal concentrations near desalination plant outlets (Sharifinia et al., 2023).

Notably, the chemical property of the brine differs based on the desalination technique used. For instance, Multi-Stage Flash (MSF) brine has a higher amount of copper contamination as the distillation process employs Cu-based alloys compared to RO brine which has a higher amount of Iron, Nickel, Chromium, and Molybdenum (Omerspahic et al., 2022). At present, desalination technologies are categorized into two main groups: thermal technologies, exemplified by MSF, and membrane-based technologies, predominantly represented RO. The RO process functions by utilizing hydraulic pressure to drive water molecules through a semipermeable membrane from the chamber with a higher salt concentration to the one with a lower salt concentration. As a result, the passage of salt through the membrane is hindered, leading to the formation of concentrated brine in the feed chamber. It's important to note that RO has a maximum water recovery level of 50% during the desalination process (Panagopoulos et al., 2019). The MSF, on the other hand, employs a multi-step process to produce freshwater from saltwater. It starts by heating the feed saltwater to its evaporation point using both the condensing vapor from the flash units and an external heat source known as the brine heater. This raises the feed temperature to a maximum of 120°C. As the high-temperature feed brine passes through a series of flash components with reduced vapor pressure and temperature, some of the feed evaporates and then condenses in the feed pre-heat exchangers. As a result, condensed water vapor forms freshwater, while highly concentrated brine is discharged from the final flash unit stage (Thabit et al., 2019). The by-product of desalination plants could have nearly twice the salt concentration or even more, reaching 70 ppt, compared to the original feed. If the brine is discharged without proper pre-treatment or dilution, the high salinity can harm the marine ecosystem, and due to its high density compared to ambient sea water, it descends to the bottom of the sea and affects the benthic community (Lattemann and Höpner, 2003). Moreover, it affects the quantity of dissolved oxygen (DO) if proper mixing of brine is not done prior to its release. Apart from high salinity, heavy metal, chlorine, acids, and anti-fouling agents, other chemicals used in the pre-treatment of feed water also contribute to causing an impact on marine chemistry (Khan and Al-Ghouti, 2021).(Table 2)

2.2. *Potential impacts of brine on marine ecosystem*

According to a study conducted by Kress et al. (2020), the discharge of brine had no detrimental impact on seawater quality, except for a fluctuating area near the seabed where salinity exceeded 1%, spanning from 2 to over 13 square kilometers with a plume size ranging from less than 1.4 to more than 4.4 kilometers. Additionally, seawater temperature increased near the outfalls, and the temperature over the plume was higher than the ambient temperature in the presence of brine. The benthic community is diverse and consists of various trophic levels, ranging from prokaryotes and microalgae to different macrofaunal organisms. As reported by Riera et al. (2012), the ecological pattern of macro-benthic fauna underwent substantial changes near a brine discharge point, but distinguishing the impact of elevated salinity from particle size distribution changes remains uncertain. Nonetheless, this influence was observed within a 15-meter radius from the discharge point, likely attributed to the impact of mixing on grain size distribution, a recognized pivotal factor in the distribution of macro-benthic fauna (Riera et al., 2012). Frank et al. (2017) reported the harmful effects of the brine on non-photosynthetic bacteria, which function as the cornerstone of the microbial food chain. The effects were characterized by increase in bacterial carbon demand (BCD) (upto 70%) after exposure to increased salinity of 5–20% during summer months. However, investigation was on the immediate effects of seawater reverse osmosis (SWRO) brine on benthic heterotrophic bacteria, it is crucial to emphasize the necessity for long-term studies at the outfall points of operational desalination facilities (Frank et al., 2017).

In an in-situ study by Sisma-Ventura et al. (2022) found that the brine acts as a vector of phosphorus as DOP from polyphosphate used in the RO, increasing the benthic heterotrophic bacteria activity, while the effect of salinity was not an issue. The impact of discharge of brine on benthic organisms can be reduced by well-designed diffuser systems (Missimer and Maliva. 2018). Indeed, polyphosphate from antiscalant delivers phosphorus in the form of DOP. Nevertheless, the use of diffusers can reduce DOP to near background levels, (Kress et al., 2020; Sisma-Ventura et al., 2022). A study suggests salinity (of 10%) along with 0.2 ppm polyphosphate-based antiscalants showed an impact of partial bleaching on 3 tested species of reef building corals (Petersen et al.,

Table 2
TDS and ion concentration in brine in different studies.

Country	TDS (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	Reference
UAE	**8747–48510**	34.1–950	220–1180	311–2660	311–17700	Ahmed et al., 2001
	73,75	781	1382	2974	23931	Mohammad et al., 2019
Spain	**55000.0**	NR	879	1864	15270	Sola et al., 2019
	1410	32	14	17	6840	Pramanik et al., 2017
Oman	**8747–48510**	43.1	414–1020	260–1980	1670–15300	Ahmed et al., 2001
Open Sea Arabian Gulf	**57400**	491	521	1738	18434	Katal et al., 2020
Spain	**79660**	781.82	960	2867	25237.28	Melian-Martel et al., 2013
Qatar	**81492**	739	725.4	2504	20993	Thabit et al., 2019

2018). When the impact of phosphonate based antiscalant on the coral *Montipora capricornis* was assessed, the results revealed significant effects on coral physiology, symbiotic microalgae, and associated bacteria (Marques et al., 2023). Notably, there was a reduction in polyp activity by approximately 25%, accompanied by tissue damage reaching 41%. Exposure to antiscalants resulted in a notable decrease in the abundance of endosymbiotic algae by 39% and concurrently upregulated the antioxidant capacity of the coral host by 45% (Marques et al., 2023). Strikingly, the polyphosphonate-based antiscalant induced coral bleaching within the two-week exposure timeframe (Marques et al., 2023). However, it is important to highlight that the referenced paper present experimental perspectives on this matter. In another study by Der Merwe et al. (2014), the sensitivity of Red Sea corals was investigated to increased salinity levels near an offshore seawater reverse osmosis (SWRO) discharge. Over a 29-day period, researchers examined the effects on *Fungia granulosa* corals, finding a notable rise in salinity and temperature directly at the discharge outlet. However, these impacts were not distinguishable from the surrounding environment at 5 m. Intriguingly, corals showed no apparent effects from varying salinity levels, as indicated by measurements of photosynthetic efficiency.

Many seagrass species, such as the Australian *Posidonia australis* are not affected by slight changes in salinity but are affected by a higher concentration of brine. The growth of germinating seedlings of *P. australis* was significantly impeded only under the 100% brine treatment, following a 7-week exposure, with a subsequent recovery period of 2.5 weeks in seawater (Cambridge et al., 2019). On the other hand, *Posidonia oceania,* one of the important species of seagrass as well as *Cymodocea nodosa* has shown sensitivity and vulnerability to salinity changes due to prolonged exposure to brine (Cambridge et al., 2019). *Posidonia oceania* was severely affected by salinity at 39.1 ppt and 38.4 ppt, while most of them died at 45 ppt within 15 days of exposure (Omerspahic et al., 2022). Heavy metals present in brine can also pose significant effect on marine environment. Increased copper and nickel levels due to brine discharge in Ras Hunjurah Lagoon, UAE, have caused the death of mangroves (Omerspahic et al., 2022).

2.3. Overview of current brine management strategies

141.5 million m^3/day volume of brine is produced from the desalination plants (Jones et al., 2019), which contain some contaminants, DOP from antiscalants, iron from coagulants, and a few other elements that are concentrated during the desalination procedure. The amount of brine produced could be equal to the amount of freshwater produced, therefore management is very important for the safety of the environment. The management of brine can be categorized into four distinct groups based on its intended use. The first category involves direct disposal or reducing/eliminating the discharge of brine. Direct disposal methods are adopted by many desalination industries, such as surface water discharge, sewer discharge, deep well injection, and evaporation pond (Ashfaq et al., 2018). However, surface water discharge of seawater brine is widely adopted by many countries due to its practicality, while also mitigating environmental impact through dilution with regular seawater or cooling water. Recent strategies of using diffusers substantially reduce the brine salinity while mixing with seawater to values of < 10% excess salinity from the background levels. In addition, diffusers maintain the pH at standard seawater acidity (Jacobson et al., 2023). Conversely, other methods such as sewer discharge, deep well injection, or evaporation ponds are commonly employed for brackish water desalination. Evaporation ponds, consisting of shallow, lined earthen basins, utilize direct solar energy to facilitate the gradual evaporation of brine. Upon evaporation of freshwater, mineral constituents in the brine precipitate into salt crystals, which are periodically collected and removed from the site. The widespread adoption of evaporation ponds in arid and semi-arid regions is attributed to their reliance on solar energy as a sustainable resource. The selection of this approach is contingent on diverse factors, encompassing climatic conditions, land accessibility and cost, as well as the quality of the underlying groundwater aquifers (Panagopoulos et al., 2019). This technique may be particularly effective in countries like Qatar, where there is abundant solar energy (Ashfaq et al., 2018). In Australia, 60% of the brine is disposed of as surface water discharge, while the United States accounts for 45%, in contrast to other disposal methods like sewer discharge, deep well injection, land application, and evaporation pond (Panagopoulos et al., 2019). Another method involves using phytoremediation, where plants such as halophytes are grown using desalination effluent (Ashfaq et al., 2018). In USA 7% of brines are disposed to evaporation pond. (Panagopoulos et al., 2019). For brine reduction, zero-liquid discharge (ZLD) approach is determined in many countries (Al-Absi et al., 2021).

ZLD is a new approach to producing fresh water using desalination technologies without generating liquid wastes, with a feed recovery rate of 95–98%. ZLD generates solid waste, which can be further processed, and the water produced can be used for various purposes such as irrigation, and drinking water (Khan and Al-Ghouti, 2021). Despite being an expensive technology, the shortage of fresh water, the hazardous effects of direct brine disposal in marine environments, and strict environmental regulations have fueled efforts to implement ZLD in desalination plants (Yaqub and Lee, 2019). MSF and RO are two technologies used in the ZLD system. In thermal ZLD systems, desalination discharge is pretreated, which includes brine undergoing filtration, pH adjustment, de-aeration, and anti-scaling of the brines. After pretreatment, the discharge is concentrated in a brine concentrator and is further processed in a crystallizer to produce distillates. The solids can either be recovered or further sent to an evaporation pond. The resulting water is recycled as clean, fresh water for human use (Muhammad and Lee, 2019). RO-based ZLD systems essentially combine conventional ZLD with RO to reduce the volume of brine slurry before it enters the brine concentrator or crystallizer. This reduction in volume cuts energy consumption in half, making it an economically viable option for desalination projects. A hybrid desalination process with both technologies in one unit or sequential steps (Loutatidou et al., 2017) is also in commercial use. Nanofiltration, vapor compression, membrane distillation (MD), forward osmosis (FO), humidification-dehumidification, and many new technologies have been developed (Loutatidou et al., 2017) for recovery of water from brine.

Electrodialysis (ED) is a desalination process that can be also used for desalination discharge remediation. It is a technique that involves a semi-permeable membrane and voltage power. This technology is used to separate inorganic ions present in solutions such as brine by applying a current, and an electrical voltage gradient is formed. ED consists of a cation exchange membrane (CEM) placed between alternating cells and an anion exchange membrane (AEM) positioned between the anode and the cathode. As a result of these gradients, anions migrate towards the opposite side, while cations are drawn towards the cathode. Thus, concentrated salts are separated from the brine solution, giving fresh water as a by-product (Panagopoulos et al., 2019). ED can remove excessive salt levels from the desalination discharge, but the performance depends on factors such as salt concentration, membrane efficiency, and operational setting. Achieving substantial elimination for specific contaminants or trace elements may require additional treatment steps or modifications to the process.

The second category of brine management focuses on recovering salt for commercial purposes. To mitigate the environmental impact of brine disposal from MSF and RO plants in Qatar, the restoration of mineral salts is recommended. Recovering salts as well as minerals is a beneficial approach to bolstering the country's economic system. Several salts, including sodium chloride, gypsum, calcium chloride, and sodium sulfate, could be retrieved from brine (Ashfaq et al., 2018). Techniques like zero liquid discharge (ZLD), have been utilized for salt recovery.

The third category involves utilizing brine for industrial purposes. A valuable approach to managing brine is its potential reuse in various applications. An illustrative case is the recent instance of reusing brine for farming of marine animals, subsequently and then irrigating shrubs in Brazil (Sanchez et al., 2015). Qatar and other countries seeking to expand their economic horizons and create new revenue streams achieving both ecological and financial advantages by repurposing brine. Implementing this approach can be further improved by replacing fish farming with microalgae production, which can be harnessed as a sustainable energy source (Ashfaq et al., 2018). Brine is a novel approach in algaculture utilization (Volkmann et al., 2007; Zarzo et al., 2014; Matos et al., 2021).

The final category involves recovering desired metals from the brine. Various pretreatments and other processes have been proposed in the recovery of various metals from brines (Peterskova et al., 2012; Semblante et al., 2018; Katal et al., 2020). Kolluri. (2003), used lime treatment to eliminate elevated levels of silica from brines, achieving a success rate of 53–76% (Katal et al., 2020). Once silica was removed, other metals were recovered by coprecipitation with $Mg(OH)_2$, followed by the removal of Calcium as $CaCO_3$ (Gabelich et al., 2007). The softened brine has been found to recover 80% of water. If the Ca $^{2+}$ is precipitated from the desalination discharge, it can achieve a water recovery of 95% (Semblante et al., 2018).(Fig. 1)

3. Microalgae-based treatment of brine

Microalgae are unicellular photosynthesizing microorganisms that play crucial role in marine ecosystems. They are capable of converting sunlight, carbon dioxide and nutrients into biomass through photosynthesis. They have been rigorously investigated for their role in wastewater treatment (Gonzalez-Camejo et al., 2019; Honda et al., 2012; Xu et al., 2015; Gao et al., 2016; Zhen-Feng et al., 2011). These photosynthetic microbes present substantial potential for remediation of desalination brine due to their ability to tolerate high salinity (Table 3). Various algal species such as *Chlorella vulgaris* (Matos et al., 2015b), *Spirulina* (Volkmann et al., 2007; Matos et al., 2021; Mata et al., 2020), *Tetraselmis suecica* (Zarzo et al., 2014), *Dunaliella* (Yildirim et al., 2022; Shirazi et al., 2018; Zhu et al., 2018; Hussein et al., 2015) and *Nannochloropsis* (Matos et al., 2015a; Shirazi et al., 2018) have been grown successfully in brine. In most studies, the brine of brackish groundwater is diluted, by mixing with conventional media *Nannochloropsis* (Matos et al., 2015a; Shirazi et al., 2018; Mata et al., 2020; Matos et al., 2018; Matos et al., 2021; Deamici et al., 2024). *Chlorella vulgaris* gave high biomass

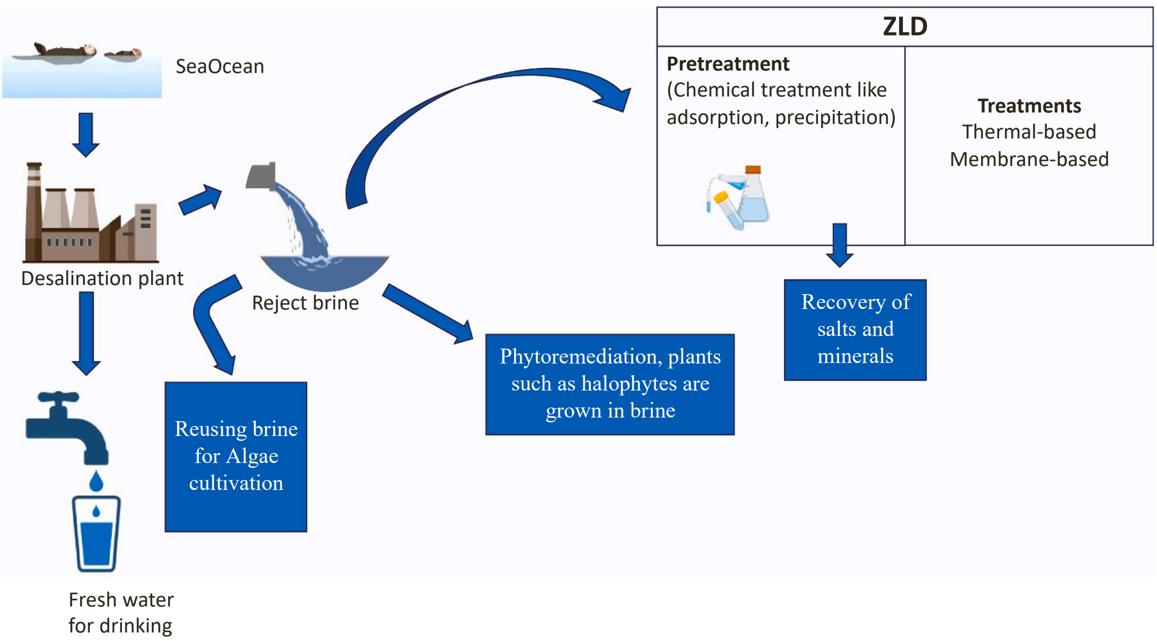

Fig. 1. Illustration depicting various brine management approaches.

Table 3
Published results on microalgae cultivation on desalination.

NO	Type of brine	Microalgae	Type of reactor	Biomass productivity	Dilution	Reference
1	Brackish water RO brine desalination plant	*Pavlova lutheri*	Raceway	4.18 g m^{-2} d^{-1}	100% crude brine, supplemented with phosphorus, trace elements and vitamins to level of F2 media	Zarzo et al., 2014
2	Brackish water RO brine desalination plant	*Chlorella vulgaris*	Fiber photobioreactor	0.09 g L^{-1} d^{-1}	25% brine: 75% BBM (bold basal medium)	Matos et al., 2015b
3	Brine from desalination plant	*Nannochloropsis gaditana*	300-mL Erlenmeyer flasks	0.135 ± 15 g L^{-1} d^{-1}	different concentrations (25%, 50%, 75% and 100% of brine) mixed with F/2 medium.	Matos et al., 2015a
4	Brackish water RO brine desalination plant	*Nannochloropsis oculata and Dunaliella tertiolecta*	Batch cylindrical glass UTEX photobioreactors	*D. tertiolecta* 0.14 g L^{-1} d^{-1} *N.oculata* 0.16 g L^{-1} d^{-1}	50:50 (combination of Brine and F/2).	Shirazi et al., 2018
				D. tertiolecta 0.19 g L^{-1} d^{-1} *N.oculata* 0.18 g L^{-1} d^{-1}	100% Crude brine	
5	Brackish water RO brine desalination plant	*Arthrospira (Spirulina) platensis*	Raceway pond	10.41 g m^{-2} d^{-1}	60% brine mixed with Paoletti Synthetic Medium (PSM) medium.	Matos et al., 2021
			100 L fiber Photobioreactors	-		
6	Seawater Desalination brine	*Dunaliella salina*	Floating photobioreactor	0.111 g L^{-1} d^{-1}	Seawater desalination concentrate treated with sodium carbonate to remove Ca^{2+} and Mg^{2+}, bubbled with CO2 for pH adjustment and carbon replenishment, and nutrients were added.	Zhu et al., 2018
7	Brackish water brine desalination plant	*Arthrospira (Spirulina)*	Raceway pond	0.05 ± 0.01 g L^{-1} d^{-1}	100% wastewater supplemented with 25% of Zarrouk constituents	Mata et al., 2020
8	Brackish water RO brine desalination plant	*Chlorella vulgaris*	Raceway pond	8.56 g m^{-2} d^{-1}	25% brine: 75% BBM	Matos et al., 2018
9	Brine from seawater desalination plant	*Arthrospira (Spirulina) platensis*	4 L Photobiorreactor	0.225 (±0.042) g L^{-1} d^{-1}	50:50 (combination of Brine and PSM)	Volkmann et al., 2007
10	Sea water RO Desalination brine	*Nannochloropsis* sp	Photobiorreactor	0.05 ± 0.016 g L^{-1} d^{-1}	Crude brine with F/2 nutrients substituting 75 mg L–1 of NaNO3 with 0.5 M urea eliminating the vitamin stock solution	ElBarmelgy et al., 2021
11	Sea water Desalination brine	*Arthrospira platensis* and *Scenedesmus sp*	flask	-	Crude brine with 100% concentration 50% crude brine mixed with 50% distilled water	Mehdipour et al., 2023
12	Brackish water RO brine desalination plant	*Ankistrodesmus fusiformis* IBLC 111	Erlenmeyer flasks (250 mL)	43.09 ± 0.01 g L^{-1} d^{-1}	Crude brine with 100% concentration	
				71.12 ± 0.02 g L^{-1} d^{-1}	50% crude brine mixed with 50%	Deamici et al., 2024
				61.01 ± 0.01 g L^{-1} d^{-1}	25% crude brine mixed with 75%	

only when grown in 25% dilution of brine mixed with bold basal media (BBM), while in dilution 30–35%, it resulted in growth inhibition (Matos et al., 2015b). *Spirulina platensis* grew well on brine at 50% dilution (Volkmann et al., 2007) and *Nannochloropsis gaditana* at 75% dilution (Matos et al., 2015a). The desalination wastewater of brackish waste requires mixing with a conventional medium because certain microalgae cannot thrive in desalination concentrate (DC) due to the elevated mineral salt strength. However, *Nannochloropsis occulata* and *Dunaliella ertiolecta* grew better in 100% crude brine than in a 50:50 medium (a combination of f/2 and crude brine in a ratio of 50:50). Crude brackish water desalination brine added to 25% of the Zarrouk nutrients was used to grow *Spirulina* sp. LEB 18 in outdoor raceway pond. The *Spirulina* sp. LEB 18 was efficiently utilized, with very good removal efficiency of NO_3^- (96.99%) and PO_4 (83.11%). Simultaneously, high-value biomolecules were produced for multiple applications (Mata et al., 2020).There are some studies which have used crude brines from seawater desalination plant (Ortega Mendez et al., 2012; ElBarmelgy et al., 2021; Mehdipour et al., 2023). This phenomenon may arise because the nutrients such as trace elements and phosphorus from phosphonates (Wang et al., 2020) within the desalination brine have the potential to foster algal growth. In study by Mehdipour et al. (2023), the highest removal of efficiency of nitrate and phosphate by *Scenedesmus sp.* in 100% brine concentrate than in 50% brine. Improved results from concentrated brine, compared to diluted ones, provide insights for large-scale cultivation of microalgae in brine.

Zhu et al. (2018), used seawater DC to cultivate *Dunaliella salina* using low cost floating photobioreactor, resulting in a biomass concentration like artificial seawater media, and 14.3 g β-carotene was generated from 1 m^3 brine. In another study the carotene production was 20.93 g m^{-2} d^{-1} for *Dunaliella salina* strain Janubiense-ITC5.10, when cultivated in SWRO, making it an optimal medium for the cultivation, along with the remarkable property of nutrient sequestration up to 99 and 71% of NO_3^- and PO_4^{-3} (Ortega Méndez et al., 2012).

Microalgae have been found beneficial in producing high biomass, giving various important by-products such as bioethanol, biodiesel, linoleic acid, and protein for animals, thus have attracted many scientists toward it (Fig. 2).

4. Mechanisms used by microalgae for Brine bioremediation

Microalgae have shown to be a successful bioremediation method for high salinity wastewater, as they are capable of removing various pollutants, including nutrients, organics, micropollutants and heavy metals (Vo et al., 2020).

4.1. Nutrient recovery from brines

According to Mehdipour et al. (2023), *Scenedesmus sp.* was found to consume significant amounts of nitrogen and phosphorus (82.95%), and nearly 100% iron in crude seawater desalination wastewater. In different research, *Picochlorum atomus* was tested under varying salinity levels ranging from 2 to 36 ppt. The data revealed that it was efficient in consuming nitrogen at a rate of 34.079 mg-N/(g-cell)(day), reducing it to half when the salinity exceeded 36 ppt. Additionally, it was able to uptake phosphate at a rate of 1.3–2.4 mg/L.d, which later decreased to 0.8–1 mg/L.d (von Alvensleben et al., 2013). *Spirulina sp.* LEB 18 was cultivated in an outdoor raceway pond using crude desalination brine supplemented with 25% of the Zarrouk nutrients. The utilization of *Spirulina sp.* LEB 18 demonstrated high efficiency, particularly in the removal of NO3– (96.99%) and PO4 (83.11%).

4.2. Removal of organics from brines

Algae have the potential to eradicate organic pollutants from water through two processes: bioaccumulation and biodegradation. Bioaccumulation involves the uptake and storage of particular organic and inorganic elements within the cells of living organisms, including algae. Biodegradation, on the other hand, happens naturally whereby organic substances are degraded by microalgae or other organisms into less complex constituents. Biological processes are the main means by which organic pollutants are transformed and degraded, and the result can be mineralization or the complete conversion of the contaminant to inorganic mineral components. Algae are particularly effective at removing organic pollutants from water and can have significant impact on remediation of adulterated aquatic environments (Baghour, 2019). In RO systems, phosphonates are organics, commonly employed as antiscalants for controlling membrane scaling. They are introduced into the RO influent at concentrations typically ranging from 1 to 15 ppm, the

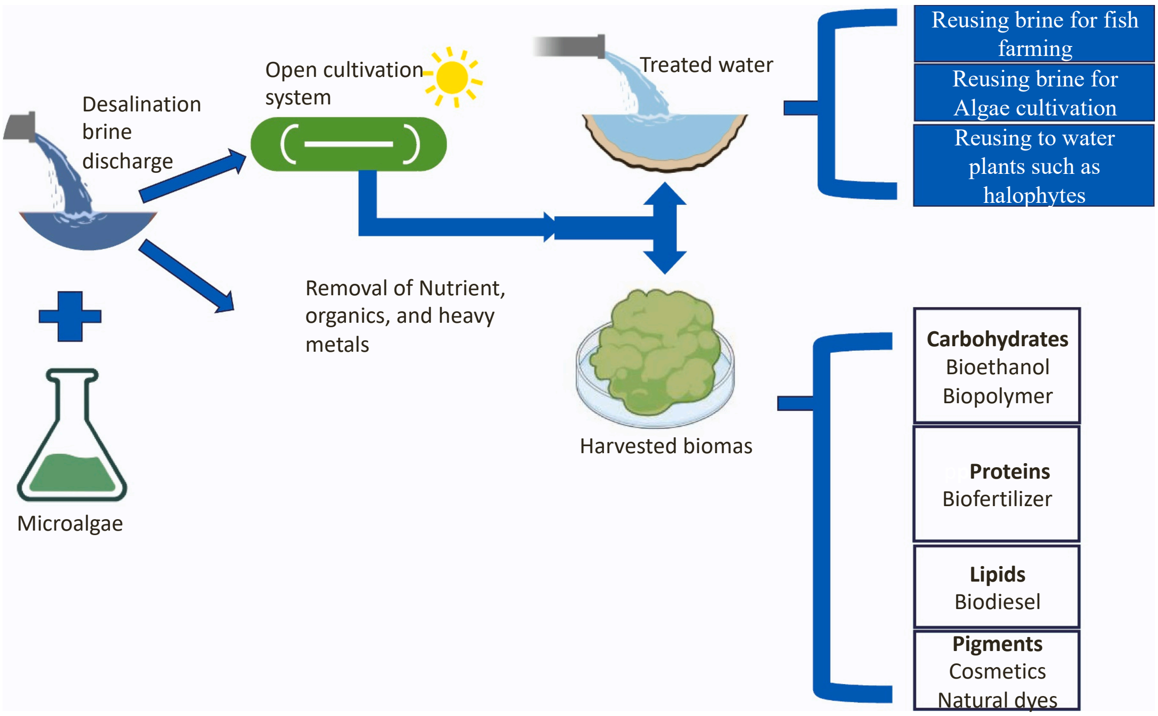

Fig. 2. Microalgae-based treatment of brine.

concentration increases to 5-folds if the recovery rate is 80% (Wang et al., 2020). *Spirulina spp*. was studied for its ability to metabolize a phosphonate, where the compound served as the sole source of phosphorus, not nitrogen, for growth. The outcome was the achievement of normal growth (Forlani et al., 2011). *Scenedesmus sp.* LX1 microalgae when initially cultured under phosphorous-starvation conditions for a period of two days and subsequently, the microalgae were cultivated in reverse osmosis (RO) concentrates, with a phosphorus source provided by amino trimethylene phosphonic acid (ATMP) antiscalant. Remarkably, the algae exhibited normal growth under these conditions utilizing phosphorus from ATMP (Huang et al., 2022).

4.3. Removal of heavy metals from brine

Microalgae consume various major element like boron, manganese, molybdenum, iron, and zinc for their cell metabolism. Few studies have addressed the occurrence of heavy metals, particularly copper (Cu), in desalination brine effluents and seawater (Omerspahic et al., 2022). In contrast, Multi-Stage Flash (MSF) technology utilizes corrosion-resistant stainless steel and non-metal equipment. Reverse Osmosis (RO) brine discharges typically contain trace amounts of metals like iron, nickel, chromium, and molybdenum. However, copper contamination is more common in MSF effluents due to the use of Cu-based alloys in the distillation process (Omerspahic et al., 2022). Although several heavy metals cause toxicity to microalgae, they possess phenomenon hormesis where low concentration of heavy metals cause them to grow and metabolize more (Sun et al., 2015). Mechanisms employed by microalgae in the remediation of heavy metals in wastewater or brine are biosorption, bioaccumulation (absorption) and metal detoxification.

4.3.1. Biosorption

Biosorption is a process employed by microalgae for the extraction of metallic toxins and salts from wastewater or saline environments, contributing effectively to treatment (Bilal et al., 2018; Abdelfattah et al., 2022; Kusuma et al., 2024). While there are currently no specific studies on desalination, the mechanism described above suggests potential applicability in brine treatment scenarios. Adsorption, complexation, surface precipitation, and ion exchange are some of the mechanisms involved in biosorption (Fig. 3). Ion exchange is the key process in removing salts and heavy metals (Patel et al., 2021; Bilal et al., 2018). The heavy metal ions are replaced with ions present on the surface of algal cells. Another important mechanism for biosorption is complexation, which occurs between reactive groups like carboxyl, hydroxy, thiol, phosphate, amino and hydroxyl-carboxyl, and salt ions by electrostatic attraction or covalent bond. The type of reactive species depends upon the species of algae as well as the cell wall structure (Kaplan, 2013; Leong and Chang, 2020). Interestingly, many scientists confirmed that not only living cells but also dead ones have the ability to accumulate heavy metals in their cells by biosorption (Cheng et al., 2017).

Various parameters like pH, temperature, initial metallic strength, time of contact, and types of ions present are responsible for biosorption (Bulgariu and Bulgariu, 2012). Out of all, pH plays a very crucial function in the adsorption of heavy metals. A slight increase in pH increases biosorption, but when it is increased a lot, then precipitation might occur. A study conducted by Bulgariu and Bulgariu. (2012), found biosorption of heavy metals Pb(II), Cd(II), and Co(II) is highly dependent on pH. Another important factor is

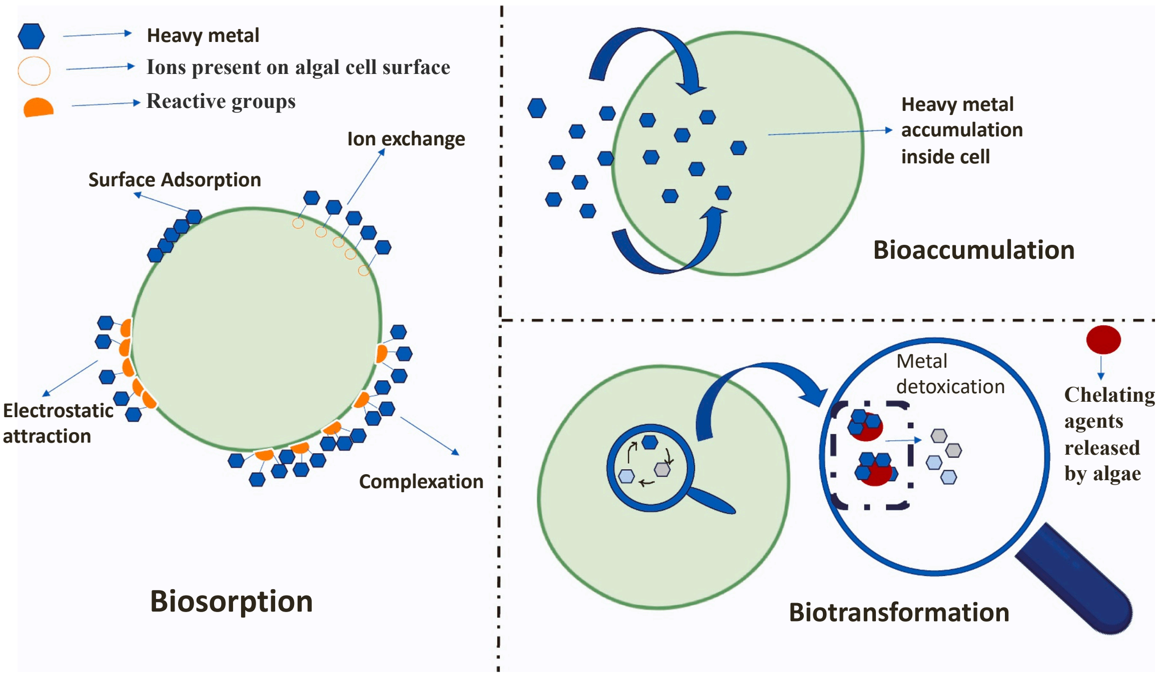

Fig. 3. Microalgae-mediated heavy metal remediation.

temperature, slight changes alter thermodynamics and thus affect the biosorption phenomenon. In the endothermic process, adsorption increases by elevating the temperature, but the opposite takes place in the exothermic process (Bilal et al., 2018). Contact time as well plays a significant role in biosorption, in which increasing the time of contact between metallic ions and algal cell increases the biosorption. However, after some time it becomes constant as no active sites are available for adsorption. This was experimentally proven when the adsorption on green algal cells for the heavy metals Pb(II), Cd(II), and Co(II) increased with increasing the contact time, but after 30 minutes the biosorption rate gradually decreased (Bulgariu and Bulgariu, 2012).

4.3.2. Bioaccumulation

Another important mechanism for the uptake of heavy metals or salts is absorption or bioaccumulation. This occurs strictly in the living stage of algae unlike biosorption, which could take place even after cell death. The process is slow comparatively, as the metal ions after getting inside the cells are transported to cell organelles, with the help of ion-selective transport proteins of the cell membrane. The process requires a lot of energy and thus occurs only in living cells. Since small algal cells have a larger surface volume ratio, high amounts of heavy metals get accumulated inside the cells (Fig. 3). Although specific studies on desalination are currently lacking, the outlined mechanism implies potential suitability for applications in brine treatment scenarios.

4.3.2.1. Metal detoxification (Biotransformation). This process is a type of self-defense of algal cells to guard individually from the toxicity caused by heavy metals. When metal ions are inside the cells of algae, they are converted to non-toxic compounds by the chelators, which link themselves to heavy metals and form compounds that are non-toxic. These chelating agents have been released by algae as a mechanism of defense against heavy metals (Genchi et al., 2020) (Fig. 3). There are various chelating agents secreted by these cells including organic acids, enzymes, peptides, and thiol-containing molecules (Chugh et al., 2022). As an instance, *Phaeodactylum tricornutum* releases a peptide chelating agent metallothioneins to detoxify heavy metals like cadmium, zinc, copper, lead, and other heavy metals. Metallothioneins bind to Cadmium more effectively compared to other metals, and form complexes with sulfide ions to enhance the stabilization of the complex. The complex ends up going to the vacuoles of the cell (Perales-Vela et al., 2006).

5. Microalgae culture systems for bioremediation of brine

Microalgae culture systems offer a promising avenue for the simultaneous bioremediation of brine and high-value biomass production. These systems harness the natural capabilities of microalgae to thrive in saline environments while absorbing contaminants from the brine. By leveraging the metabolic activities of microalgae, this approach holds the potential for mitigating the environmental impact of brine discharge from seawater desalination plant (Mehdipour et al., 2023; Zhu et al., 2019). To enable bioremediation at an industrial scale, microalgae can be cultivated using various systems that meet specific criteria such as being cost-effective, having sufficient sunlight exposure, capturing CO_2, and providing quality and quantity of nutrients. The selection of the system is highly

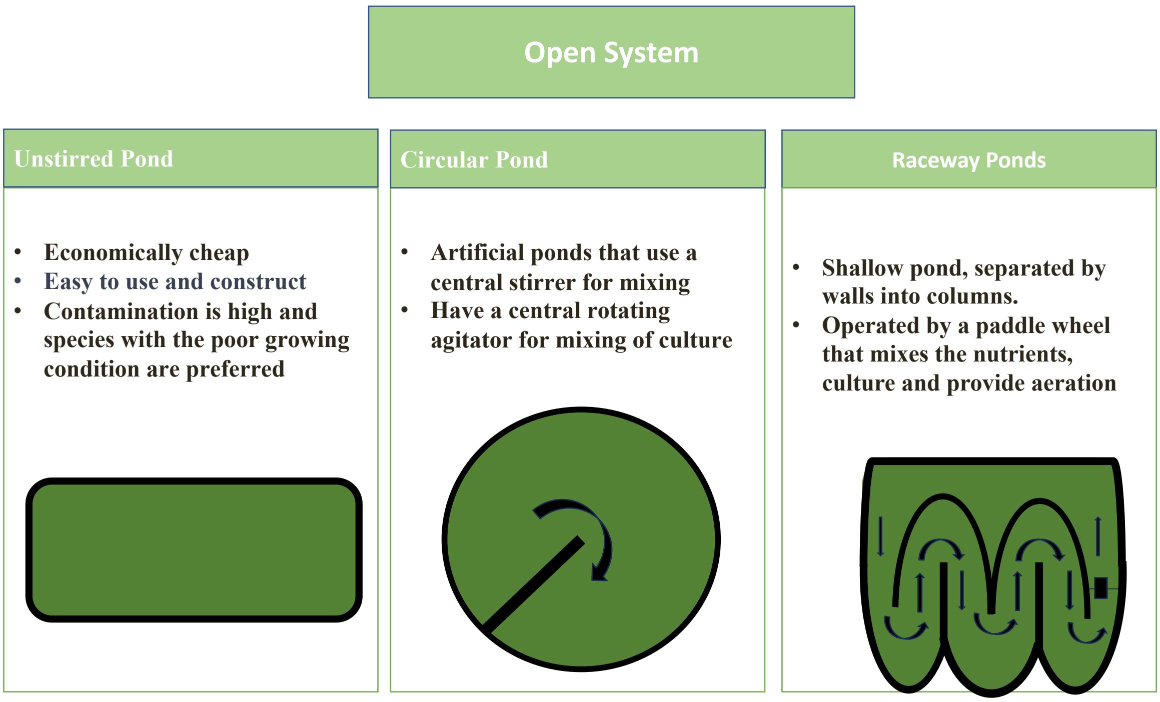

Fig. 4. Open culture systems for algae-based brine-bioremediation.

dependent on several elements like the type of microalgae species being grown, climatic conditions, and external factors (Arutselvan et al., 2022).

Open systems are generally used for different types of wastewater treatment (Zhu et al., 2017) including one from desalination plant (Matos et al., 2018; Matos et al., 2021; Mata et al., 2020). Open type of system as the name suggests is a lookalike of a natural pond and depends upon the natural sunlight and local climate which determines temperature and evaporation.

Its construction is feasible and cost-effective, with the advantage of easy to scale up for large-scale brine bioremediation. There are various configurations for open systems, depending on their dimensions, construction materials, agitation systems, and angle of inclination. Open system has a limitation of contamination by flies, insects, and other external species, limited light penetration, inefficient transfer of gas and liquid, lack of control over operating conditions, and lower microalgal biomass concentration in the final product (Rayen et al., 2019). Besides, due to water loss by evaporation, water maintenance also becomes a problem (Arutselvan et al. 2022). They are of different types that includes big shallow ponds, tanks, circular ponds, and raceway ponds (RWP) (Arutselvan et al. 2022) (Fig. 4).

The RWP system is a shallow pond, separated by walls into columns, and is operated full-time or part-time by a paddle wheel, which mixes the nutrient and the culture (Zhu et al., 2017). The RWP used by Mata et al. (2020) in cultivation of *Spirulina* sp. LEB 18 in desalination brine of brackish groundwater obtained from an artesian well had a length, width and height of 2.20, 0.90 and 0.35 m. In another study of *Spirulina* cultivated in brine of brackish groundwater using raceway pond, had an area of 8 m^2, 5.0 m length, 1.6 m width, 0.5 m depth and total capacity of 4000 L/4 m^3 (Matos et al., 2021). The paddle wheel in race ponds is to mix the nutrients, cells and provide aeration. A good amount of CO_2 usage is required for efficient biomass production. This method is cost effective only if the land and water is free, otherwise construction of pond is quite expensive (Zhu et al., 2017).

6. Achievements in Micro-Algae-Based Brine Remediation

This approach appears premature and is unlikely to serve as a comprehensive solution for sea disposal of brine; rather, it seems more suited as an additional option for small-scale operations. The achievement includes nutrient uptake from brines and biomass valorization generated during micro-algae-based desalination discharge remediation at small-scale. The biomass produced is of high value and can be utilized for various purposes.

6.1. Nutrient sequestration by microalgae from brines

Microalgae have exhibited the capability to effectively eliminate nutrients such as nitrogen and phosphorus from brines. According to study, by Ortega-Méndez et al. (2012), *Dunaliella salina* strain Janubiense-itc5.10 has shown significant nutrient sequestration up to 99 and 71% of NO_3^- and PO_4^{-3}, respectively, when grown in reverse osmosis brine derived from desalination wastewater. The strains *Myconastes homosphaera, Tetraselmis suecica*, and *Pavlova lutheri* grown in brines (2 liters flask) demonstrated remarkable reduction of nitrate up to 45, 46.84 and 22.88%, respectively (Zarzo et al., 2014), while total nitrogen removal yield by strain *D. tertiolecta* and *N. culatea* was reaching approximately up to 93% and 91%, respectively (Shirazi et al., 2018). The removal efficiency of fluoride and phosphate was higher (approaching 100%) compared to other element ions (ranged from approximately 10–20%) (Shirazi et al., 2018). *Spirulina* sp. LEB 18 have also been identified as proper candidate removal of phosphate, zinc and nitrate approximately to 83.11%, 96.43% and 96.99%, respectively (Mata et al., 2020).

The impact of performance and efficacy to microalgal bioremediation is highly dependent on brine composition. The essential nutrients for the growth of algae include carbon, nitrogen and phosphorus. Microalgae utilize carbon typically in form of carbon dioxide to produce energy and organic compounds during photosynthesis. Nitrogen being building block of protein, nucleic acid and chlorophyll is another crucial element for growth. For energy transfer, DNA, and RNA synthesis, and cell membrane formation, phosphorus is very essential. Nutrient sequestration is highly affected by the overall concentration of essential elements present in the culture medium; the uptake of nutrient is intimately related to the growth rate of algae. The growth of microalgae also necessitates minute quantities of trace elements such as zinc, copper, manganese, molybdenum, calcium, Iron, magnesium, potassium, and sodium which usually exist in excess in brines (Mohsenpour et al., 2021)

6.2. Microalgae biomass valorization after brine remediation

The biomass of microalgae is of potential importance containing a wide range of valuable compounds including lipids, proteins, carbohydrates, pigments, and bioactive compounds. There are various methods for algae biomass valorization obtained using brine media, such as extraction of valuable compounds, conversion to biofuel, and application in various industries.

6.2.1. The protein content of microalgal cells grown on brine

A study states that growing *Spirulina platensis* at 50% seawater C gave biomass with 49.5% of protein although the content in the control medium is 51% (Volkman et al., 2008). Regrettably, there is currently a lack of studies on the protein content of microalgae cultivated in 100% crude seawater brine. However, considering that brine may contain trace elements and contaminants such as antiscalants and biocides, as discussed in the previous section, employing microalgal biomass for feed purposes is not advisable. However, there are some studies of brackish water DC, which suggest that the cultivation in crude brine might significantly reduce the protein content of some microalgae. In a research analysis by Matos et al. (2015b), *Chlorella vulgaris* grown in a brackish water DC of 25% as media, the protein amount ranges from 45.3% to 51.0% in dry biomass, and the increasing the concentration of brine to 55%

led to the decrease of the protein content from 51% to 15.7%. The protein content of *Spirulina* grown in the medium by mixing 60% desalinate concentrate (DC) obtained from brackish water with 40% Paoletti Synthetic Medium (PSM) under indoor and outdoor cultivations, was in the range of 45.0 –59.0% (Matos et al., 2021). *N. gaditana* has been shown to grow in 75% brackish water DC and gave biomass with 27% of proteins but has an increased protein content of 41% in conventional media (Matos et al., 2015a). These investigations substantiate that cultivation in brine may substantially diminish the protein content of certain microalgae species. However, the salt concentration in seawater brines reverse osmosis desalination brines typically registers at 10–20% more, contrasting with brackish water brines where it is approximately an order of magnitude lower (Matos et al., 2024). The variance in desalination brine origins and the specific strain of microalgae cultivated could significantly influence protein concentration.

6.2.2. Lipid content of microalgal cells grown in brine

Microalgae make a promising feedstock for biofuel production, as they are known for their high lipid content. They have garnered the attention of researchers for their application in the nutraceutical and biofuel sectors. Several studies have shown the effect of brine on the lipid content of microalgae when grown in continuous bioreactors, or in small batches with semi-continuous cultures. Modulating the concentration of NaCl in the culture medium has been recognized as an efficacious strategy for stimulating and augmenting algal lipid content. In essence, each microalga exhibits an optimal growth salinity, with the salinity tolerance varying among distinct algal species, a characteristic intricately linked to the ecological distribution and physiological attributes of microalgae (Matos et al., 2024). The microalgae can be used for biodiesel production by growing them in brine (Matos et al., 2024). *S. platensis* was grown in 50% DC of seawater, in photoautotrophic conditions, palmitic acid, oleic acid, and γ-linolenic acid were 36.1, 20 and 14.0%, respectively (Volkmann et al., 2008). The fatty acids with C16 to C20 are very efficiently used in biodiesel production (Matos et al., 2017). Lipid content was determined to be 9.5% ± 2.1% w/w in *Nanochloropsis* cultivated in DC from seawater desalination brine with Constituents of F/2 media eliminating the vitamin stock and solution 75 mg L–1 of NaNO3 with 0.5 M urea (ElBarmelgy et al., 2021). The lipids content of *N. gaditana* was increased from 5.9% to 12.6% in dry matter, when the concentration of DC of brackish water to media was increased from 25% to 75%, as well as the saturated fatty acid was higher compared to unsaturated fatty acid (Matos et al., 2015a). In addition, the concentration of palmitic acid elevated from 29.4% to 53.4%, with a declining percentage of eicosapentaenoic acid from 12.2% to 0.2%. (Matos et al., 2015a). The increase in saturated fatty acid could be due to an adaptive osmoregulatory mechanism to cope with the increase in salinity (Matos et al., 2017). However, DC originated from an inland source characterized by a significantly lower salinity of 2.2 g L^{-1}, in contrast to salinity observed in the DC from SWRO (ElBarmelgy et al., 2021). Cultivating microalgae in crude brine, leading to an augmented lipid concentration, represents a favorable outcome, the microalgae can be used for biodiesel production by growing them in brine (Matos et al., 2024).

6.2.3. The carbohydrate content of microalgal cells grown in brine

The biomass of some microalgae grown in DC of brackish water has shown great potential in accumulating carbohydrates in its cell, making it a promising feedstock for bioethanol production. Some strains of microalgae like *Spirulina* sp. LEB 18 grown in high salinity brine supplemented with 25% Zarrouk nutrients gave high carbohydrate content (52%) compared to the strain cultivated in control (48%) (Mata et al., 2020). The carbohydrate content found was not very high (10–20%) when *Spirulina* was grown in a medium of mixing 60% brine with 40% Paoletti Synthetic Medium (PSM) (Matos et al., 2021). The strain *C.vulgaris* grown in 30% brine with 70% bold basal medium (BBM), resulted in a higher carbohydrate + fiber content compared to cells grown in BBM alone. The carbohydrates + fiber content did not reduce much, even when the concentration of brine was increased to 50% (Matos et al., 2015b). The exploration and understanding of carbohydrate accumulation in the cells of microalgae when grown in highly saline water can lay the groundwork in the production of bioethanol and biopolymer. Results from brackish water brine indicate a substantial yield of carbohydrates, whereas there is an absence of findings for seawater brine.

6.2.4. Beta carotene content in microalgal cells grown in brine

β-carotene, a red-orange pigment belonging to the group of carotenoids, is essential for of nutrition and has many benefits. It is a precursor of vitamin A and has antioxidant properties, protects from cancer, enhances immunity, and inhibits tumor formation (Yildirim et al., 2022). It is naturally found in many fruits, vegetables, and plants. Biomass enriched with a high amount of β-carotene has a very high value and would profit the desalination industry (Zhu et al., 2018).

Zhu et al., 2018, used DC of seawater to cultivate *Dunaliella salina* using low cost floating photobioreactor, resulting in biomass productivity similar to artificial seawater media, and 14.3 g β-carotene was produced from 1 m^3 desalination concentrate. In another study the β-carotene production was 20.93 g m^{-2} d^{-1} for *Dunaliella salina* strain Janubiense-ITC5.10 when grown in seawater reverse osmosis brine from desalination plant, making it an optimal medium for the cultivation, along with remarkable property of nutrient sequestration up to 99% and 71% of NO_3^- and PO_4^{-3} (Ortega Méndez et al., 2012).

7. Challenges in Micro-Algae-Based Brine Remediation

Micro-algae-based brine remediation presents a viable solution to address the environmental issues related to desalination waste. Regardless of the potential, there are various challenges that cause hindrance in successful implementation. Some key challenges include:

7.1. Brine's high salinity

The specific level of salinity is required for microalgae to prosper, and due to extremely high levels of salinity, their physiological process can get impaired. It can lead to osmotic stress, ion imbalances, and oxidative damage, negatively impacting the health and productivity of the microalgae. High salinity in the surrounding environment leads to osmotic stress on microalgae. Water moves out of the cells to balance the salinity gradient, causing dehydration and hindering normal cellular functions (Shetty et al., 2019). Excess salt in the growth medium also disrupts the balance of ions within microalgae cells. This imbalance affects ion transport mechanisms and enzyme activities, leading to disruptions in essential cellular processes. This can ultimately result in reduced growth rates and cellular damage (Shetty et al., 2019).

Different algal strains exhibit distinct preferences for specific salinity ranges, which directly influence their growth rates and biomass yields. For example, green algae tend to thrive predominantly in oligohaline and mesohaline lakes, while blue-green algae show adaptability in mesohaline and polyhaline environments. The *Chaetoceros calcitrans* strain demonstrates robust growth in marine conditions with a salinity level of 3%, whereas Chlorella sp. exhibits a preference for lower salinity, thriving best at 2.5%. These salinity preferences of various algal species highlight the importance of understanding and optimizing environmental conditions to foster their optimal growth and productivity (Vo et al., 2020).

As salinity levels rise, microalgae cells experience an influx of cations like Na+ and K^+, leading to a constraint in their photosynthesis activity. These cations interfere with the functionality of phycobilin in photosystem II and impede the transportation of electrons to photosystem I (Zhou et al., 2017). In response to the reactive oxygen species (ROS) stress, the microalga's antioxidant system is activated, giving rise to various enzymes. These enzymes act as catalysts, promoting the synthesis of hydrocarbons and pigments, which subsequently serve as an energy source for the microalgae cells. This adaptive mechanism helps microalgae cope with the challenges posed by increased salinity and maintain their metabolic activities under such stressful conditions (Vo et al., 2020).

7.2. Brine's chemical composition

Desalination brines is a concentrated saline solution, with an elevated level of salts, heavy metals, and some nutrients. The availability of the amount of nutrients such as nitrogen and phosphorus, which is crucial for the growth of algae is not present at appreciable concentrations compared to wastewater. The presence and balance of nutrition widely impact the bioremediation process (Mohsenpour et al., 2021) of brines. Additionally, the brine may contain various components including biocides, surfactants, scale inhibitors, and solid residues, produced because of filter backwashing. These chemicals are toxic, and their presence creates environmental hazards. Chemicals, like phosphonate-based antiscalants and ferric (or alum) sulfate-based coagulants, derived from the desalination process itself are also found in brine (Omerspahic et al., 2022). Phosphonates, heavily used antiscalants in the desalination industry are usually considered safe for aquatic animals, but their impacts on microalgae remain a matter of controversy. Growth inhibition on *Scenedesmus* sp. LX1 was observed after a 10-day exposure period half maximal effective concentrations of 57.6 mg/L for Hydroxyethylidene diphosphonic acid also known as etidronic acid (HEDP) and 35.7 mg/L for diethylenetriamine penta (methylene) phosphonic acid (DTPMP) (Wang et al., 2020). The phosphonates showed weak influences on *Scenedesmus* sp. LX1 in the first 4 days of cultivation. In contrast, significant growth inhibition was observed subsequently with half maximal effective concentrations of 57.6 and 35.7 mg/L for HEDP and DTPMP, respectively. The existence of phosphonates in brine inhibited the absorption of iron ions by micro-algae for the formation of complexes. This resulted in an extreme deficiency of iron, impeding photosynthetic activity. Consequently, the deficiency further led to a reduction of chlorophyll content, which is crucial for photosynthesis (Wang et al., 2020).

7.3. Algal biomass harvesting

After the algae cells have absorbed the pollutants from the brine, the biomass generated needs to be harvested for further valorization. Nonetheless, the minute and delicate algae cells can be challenging to separate from the growth medium. The achievement of widespread financial efficiency in brine remediation faces a significant hurdle, the development of a cost-effective and sustainable harvesting process (Plöhn et al., 2021). This challenge arises due to the inherent buoyancy of many microalgae, which restricts their settling through gravitational forces alone. Life cycle analysis indicates that the retrieval of microalgae from the liquid stream alone contributes to approximately 20–30% of the overall expenses (Plöhn et al., 2021). Generally, the higher efficacy in harvesting cells is demonstrated by physical techniques, the major drawback is their increased cost. Various economically feasible chemical methods offer reliable and energy-efficient harvesting of microalgae biomass on a wider scale in less time but are limited by the problem of biomass contamination (Huang et al., 2023a, 2023b). Most of the biological methods require an extended incubation period for the formation of flocs, thus utilization of bio-flocculation is presently restricted and in its nascent stages of advancement. To achieve untainted and premium-grade bioproducts from microalgal biomass, the adoption of natural and exceedingly efficient biological harvesting methods is undoubtedly the optimal approach and harbors immense potential as a viable solution (Huang et al., 2023a, 2023b).

8. Future approaches (research trends) in microalgal biomass grown in brine

Future research trends in microalgal biomass grown in brine include enhancing strain halotolerance through genetic engineering techniques, exploring novel microalgae strains for enhanced bioremediation efficiency and optimizing biotechnological applications to extract value from the biomass including, pharmaceuticals, nutraceuticals, biorefinery, biogas, and biochar (Fig. 5).

8.1. Strain selection and optimization

Microalgal strains, including *Scenedesmus* (Mehdipour et al., 2023), *Spirulina* (Matos et al., 2021), *Dunaliella* (Zhu et al., 2018), *Nannochloropsis sp* (ElBarmelgy et al., 2021), *Ankistrodesmus fusiformis* (Deamici et al., 2024), have been systematically utilized for the remediation of brine environments, concurrently yielding biomass of exceptional quality. These strains, renowned for their adaptability and physiological characteristics, exhibit promising potential in addressing brine-related challenges while producing biomass with valuable properties. This strategic exploitation of diverse microalgal strains underscores their significance in contributing to both brine management and the generation of high-quality biomass. Underlining high salinity, high temperature, and biotopes found in brine evaporation sites (Hosseini, 2022), these efforts focus on identifying microalgae species that exhibit natural adaptability to the challenging environmental factors prevalent in the region (Hosseini et al., 2021). By focusing on indigenous microalgae from extreme conditions, this research has the potential to unlock new, resilient and high-yielding microalgae strains, that could be used for sustainable and efficient biomass production. Some potential avenues for future research and development includes identifying and developing fast growing microalgal strains that can thrive in high salinity and produce high quality biomass. Fast-growing halophilic strains such as *Picochlorum* can be considered as good candidate for brine bioremediation as it showed interesting capabilities to sequester salt and use it for their growth (Dahlin and Guarnieri, 2021). This converges with previous findings of Ridley et al. (2018) who demonstrated that *Picochlorum tricornutum* exhibits rapid growth and high tolerance to nitrate concentrations 100 times higher than those in standard media.strains like Scenedesmus, spirulina, nanoclopsis, duniella have been exploited for brine remediation and obtaining high quality biomass. Furthermore, the potential of these strains can be enhanced through genetic engineering by identifying and transferring genes responsible for specific traits such as salinity tolerance, interesting lipid productivity and efficient nutrient sequestration from brine (Sreenikethanam et al., 2022).

8.2. Carbon capture

By coupling the microalgae cultivation process with carbon dioxide sequestration, researchers can explore the potential to mitigate greenhouse gas emissions while simultaneously promoting microalgal biomass production (Ighalo et al., 2022). This approach capitalizes on the inherent ability of microalgae to capture CO_2 during photosynthesis, presenting a unique opportunity for mitigating greenhouse gas emissions while concurrently producing valuable biomass (Schipper et al., 2019). The process unfolds by cultivating microalgae in brine-rich settings, offering not only essential nutrients but also a controlled environment for growth (Hussein et al. 2015). As these microorganisms' flourish, they engage in photosynthesis, utilizing sunlight, water, and atmospheric CO_2 to synthesize energy-rich organic compounds. Crucially, the captured CO_2 becomes incorporated into the microalgal biomass, which consists of carbohydrates, lipids, and proteins (Onyeaka et al., 2021). The proposal to employ algae for CO_2 fixation not only presents an avenue to reduce the amount of CO_2 from flue gases released by power plants (Naď et al., 2023) but also holds potential for addressing greenhouse gas (GHG) emissions (Zhao et al., 2024). By integrating algae into the process of flue gas treatment, particularly in the context of brine remediation, has a synergistic approach of reducing the amount of CO_2 in flue gases, contributing to cleaner emissions, and the potential of algae to produce biomass in brine. This innovative approach aligns with sustainable practices, offering a multifaceted solution that addresses both carbon capture from industrial processes and brine disposal challenges.

8.3. Nutrient recycling and sustainability

Nutrient recycling and sustainability are crucial aspects of microalgal biomass production, especially when using desalination brines as growth media (Mehdipour et al., 2023). To reduce the environmental impact of microalgal cultivation, researchers need to

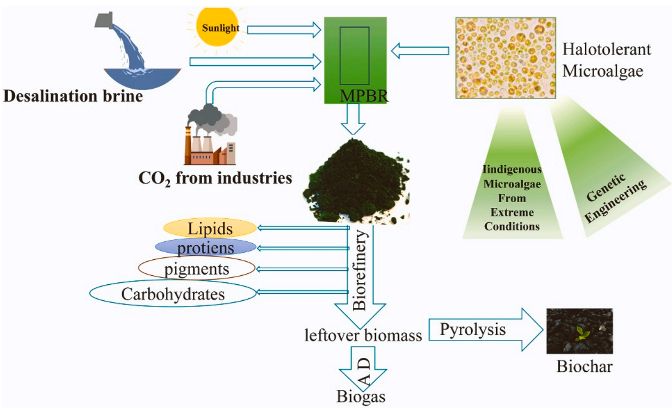

Fig. 5. Future research trends for microalgal biomass grown in brine. AD: Anaerobic digestion.

explore ways to recycle nutrients and waste products. One promising avenue involves the integration of diverse waste streams from various industries, such as aquaculture and brine, to serve as nutrient sources for microalgae (Han et al., 2018). This holistic approach strives to establish closed-loop systems that harness the synergies between waste utilization and biomass generation. One innovative approach within the realm of nutrient recycling is the utilization of alternative nitrogen sources, such as urea, agricultural wastes (Khan et al., 2023a, 2023b) or waste nitrogen fertilizer from fertilizer industry (Al-Jabri et al., 2021).

Nitrogen is a vital nutrient for microalgal growth, and its sustainable sourcing is of paramount importance (Kumar and Bera, 2020). Urea, a nitrogen-rich compound commonly found in agricultural fertilizers, can potentially be repurposed as a nitrogen source for microalgae cultivation. By incorporating urea into the growth medium, microalgae can utilize the nitrogen present in urea to fuel their growth (ElBarmelgy et al., 2021). This practice not only offers a sustainable nitrogen supply but also contributes to the recycling of agricultural waste products. The advancement of nutrient recycling and sustainability in microalgal biomass production, particularly in the context of using desalination brines, is underpinned by the innovative integration of waste streams from diverse industries. Incorporating alternative nitrogen sources like urea, agricultural wastes, aquaculture effluents, and wastewater into microalgal cultivation systems creates closed-loop solutions that minimize resource consumption, promote circular economies, and reduce the environmental impact of both waste generation and microalgal cultivation (Khan et al., 2023a, 2023b).

8.4. Photobioreactor design and membrane photobioreactor

In addition to biomass production, future approaches may involve the development of microalgae-based biorefineries. This would mean utilizing all components of microalgae, including lipids, proteins, carbohydrates, and pigments, to produce a wide range of valuable products such as biofuels, nutraceuticals, and high-value chemicals (Saadaoui et al., 2018). To scale up microalgal biomass production in brine, optimizing the cultivation system will be essential including membrane photobioreactors. Future research may focus on improving the design, light distribution, and nutrient supply in photobioreactors to maximize microalgal growth and productivity (Rezvani et al., 2022). The utilization of Membrane photobioreactors (MPBRs) for cultivating microalgae in brine environments represents a promising and innovative future approach. They are a combination of cultivation photobioreactor systems and membranes. They are an emerging algal-based technology for the treatment of water from waste. MPBRs can achieve a good amount of reduction of minerals and nutrients in water, and they also produce a very concentrated amount of algal biomass. MPBR is operated in a continuous manner, with PBRs like air lift or flat panel combined with a submerged or side stream membrane filtration process. MPBR is designed in such a way that uniform light is reached throughout the culture and favorable conditions for producing good biomass is met (Luo et al., 2017). MPBR was made to tackle the problems of an open system, and to overcome the limitations of closed systems. MPBR could independently control hydraulic retention time (HRT), and solid retention time (SRT) (Luo et al., 2018). Given the limitation of other cultivation systems of algae, this technology has been a hot topic for research. MPBR has the advantage of removing excess biomass from the membrane and harvest it from the wastewater. The biomass is harvested in an easy way compared to other systems and is further processed for quality products. MPBR has wide application in various types of wastewater treatment (Huang et al., 2023a, 2023b, Khan et al., 2024, Segredo-Morales et al., 2024, Wang et al., 2024) However, its potential in brine bioremediation remains unexplored. Given the multiple benefits offered by the MPBR, its utilization in brine bioremediation warrants consideration and further investigation.

8.5. Anaerobic digestion of microalgal biomass grown in brine

One of the potential applications of microalgal biomass can be its use in anerobic digestion to produce biogas. Golueke et al. in 1957 were the pioneering authors who initially documented the anaerobic digestion of microalgae biomass, specifically Chlorella vulgaris and Scenedesmus, which were cultivated as integral components of a wastewater treatment system. Subsequently, Oswald, one of the co-authors from the original Golueke et al. research, furthered this investigation through a series of subsequent scientific publications (Oswald et al., 1994; Green et al., 1994; Chen and Oswald, 1998). Use of anerobic digestion for the biomass harvested from brines can reduce the high amount of energy input in the production process by producing the biogas. This presents an opportunity for sustainable generation of energy, and this can offer promising opportunity for the generation of sustainable energy. This idea not only manages the waste of desalination plant but also closes the loop of energy consumption, which usually increases the cost of plant. Digestate, a byproduct of anaerobic digestion, has the potential to serve as an organo-mineral fertilizer, effectively replacing traditional mineral fertilizers. This is primarily because it contains essential macronutrients like nitrogen, phosphorous, and potassium, which are crucial for plant growth and development (Alburquerque et al., 2012). Furthermore, digestate often contains valuable trace elements that are essential for the germination and growth of plants. The production of biogas from the microalgal biomass is still in the development stage and there are no studies on the use microalgae grown in desalination discharge as digestate.

Salinity can pose threat the bacteria present in the anaerobic digestion, by dehydrating them due to increased osmotic pressure. In a study by Vergara-Fernandez et al. (2008), it was demonstrated that marine microalgae of high salinity are possible, and the recorded biogas production was between 95 and 260-mL g^{-1} TS microalgae loaded using a two-stage digestion. Mottet et al., (2014) demonstrated the adaptation of *Dunaliella salina* under different salinity condition, and observed methane production from anerobic digestion of its biomass at 35 g/L of salinity (Wu et al., 2019). However, Ridley et al., (2018) tested microalgae *P. tricornutum* grown in nitrate rich brine from water industry, for the production of biomethane using anaerobic digestion. The bio-methane potential of was *P. tricornutum* grown in brine 39 L kg VS^{-1}, while the biogas yield in standard F/2 media was relatively higher of about 286 L kg VS^{-1} (Ridley et al., 2018).

8.6. Utilizing microalgae cultivated in brine for biochar production

By utilizing the microalgae's capacity to capture CO_2 during growth in brine-rich environments, the subsequent conversion of harvested microalgal biomass into biochar presents a pathway for efficient carbon storage. The extraction of biochar from microalgal biomass holds significant interest, given its multifaceted applications. This bioproduct serves as a versatile material, finding utility as a filter medium in water filtration systems and acting as a bio-adsorbent in wastewater treatment processes. Its efficacy lies in the ability to efficiently remove a spectrum of both organic and inorganic contaminants, showcasing the potential for sustainable solutions in water purification technologies (Morais et al., 2023). Various microalgae, including *Chlorella*, *Arthrospira platensis*, a consortium of microalgae, and *Nannochloropsis* sp., undergo hydrothermal carbonization using different process parameters. *Chlorella*, for instance, is subjected to a temperature of 180 °C with a residence time of 30 minutes, resulting in a biochar yield of 26.32%. *Arthrospira platensis*, on the other hand, undergoes hydrothermal carbonization at temperatures ranging from 190 to 210°C, with a residence time of 2–3 hours, yielding biochar in the range of 41–67%. A consortium of microalgae, processed at 170 °C with a residence time of 10 minutes, yields an impressive biochar percentage of 77.72%. *Nannochloropsis* sp. undergoes hydrothermal carbonization at temperatures between 180 and 220 °C, with a residence time ranging from 15 to 39 minutes, resulting in biochar yields between 30% and 47% (Costa et al., 2023).

Biochar, a carbon-enriched form of charcoal derived from organic matter, is generated through the thermal breakdown of biomass under restricted oxygen conditions and at relatively modest temperatures (400–700 °C). Pyrolysis, torrefaction, and hydrothermal carbonization represent the primary methods for acquiring biochar from microalgae. With its inherent carbon retention, biochar serves as a durable adsorbent for carbon dioxide, offering a sustainable alternative to fossil fuels in industrial processes. The composition of biochar is subject to variation based on the specific raw materials employed in its production (Costa et al., 2023). Biochar consists of an ample amount of calcium, carbon, magnesium, nitrogen, and phosphorus. It can also be as a soil amendment, serving as a fertilizer to enhance soil nutrition. Numerous research studies have shown that mixing of biochar into the soil results in enhanced soil moisture retention, increased carbon content, and improved soil fertility (Lu et al., 2023). Permeable and finely textured composition of biochar, makes it suitable for soil application to retain water for an extended period. Its high surface area to volume ratio and ability to improve soil stability make it beneficial in agriculture. In comparison with alternative biochar, microalgal-derived biochar exhibits elevated levels of minerals and nutrients. Various research has indicated that the nutrient and mineral content of microalgae-derived biochar surpasses that of other sources (Lu et al., 2023). The integration of microalgal biomass into biochar production aligns with circular economy principles by transforming waste streams into valuable resources, further enhancing sustainability (Costa et al., 2023).

8.7. Techno-economic feasibility and cost analysis

Another important point to be taken into consideration is comprehensive techno-economic feasibility and potential market applications of high value biomass cultivated in desalination discharge. These analyses provide a valuable insight into the cost of cultivation, harvesting, processing and product development, and potential market application of biomass grown in brine (Rezvani et al., 2022). Cost analysis considerations involve evaluating infrastructure setup, energy consumption, nutrient supplementation, and operational expenses. Assessing the efficiency and scalability of photobioreactors, membrane systems, and monitoring equipment provides valuable insights for making informed decisions on long-term investments (Vázquez-Romero et al., 2022). Managing energy costs through renewable sources and optimizing nutrient supply are key to economic sustainability. Efficient biomass harvesting and processing methods help mitigate expenses (Khan et al., 2022).

Understanding the microalgal product demand within the market is fundamental. Researchers must assess potential markets for the biomass and its derived products on both local and international scales, estimating market size and potential revenue streams. Through comprehensive Economic and Technological Viability Studies, informed decisions regarding microalgal biomass cultivation implementation in brine, alongside desalination brine remediation, can be made (Figueroa-Torres and Theodoropoulos, 2023). These studies offer crucial insights into potential advantages, challenges, and associated risks, guiding policy formulation, attracting investments, and fostering sustainable development (Banerjee, 2019). The scale of cultivation and market demand for microalgal biomass products directly influence economic returns. Socio-economic benefits, such as job creation and waste reduction, contribute to the broader impact (Yang et al., 2015). Comparative analysis with other cultivation methods contextualizes advantages. This collective analysis is pivotal for informed decision-making, promoting economic growth while addressing environmental challenges through microalgal biomass cultivation in brine environments.

9. Conclusion

Microalgal-based bioremediation of desalination brine holds significant potential for addressing environmental concerns and creating a sustainable approach to water treatment. By harnessing the natural ability of microalgae to absorb and metabolize pollutants, this technology could become a promising solution for reducing the ecological impact of desalination plants. Through ongoing research and development, we can expect advancements in microalgal cultivation techniques, strain selection, and system optimization, leading to improved efficiency and effectiveness in remediating desalination discharge. This innovative approach also creates additional value by generating biomass for biofuel production and other valuable byproducts. As the field progresses, we can anticipate the integration of microalgal remediation as a standard practice within the desalination industry, contributing to a more sustainable and eco-friendly approach to water treatment. With continued research and development, this technology has the potential to become a standard practice within the desalination industry.

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CRediT authorship contribution statement

Mohammad A. Al-Ghouti: Writing – review & editing. **Sami Sayadi:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Hoda Ali Hosseini:** Writing – review & editing. **Isra Eqbal Gilani:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Imen Saadaoui:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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