Sustainable Water Resources Management (2023) 9:108
https://doi.org/10.1007/s40899-023-00887-2

ORIGINAL ARTICLE

Desalination concentrate microalgae cultivation: biomass production and applications

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Received: 29 August 2022 / Accepted: 5 June 2023 / Published online: 16 June 2023

Abstract
The environmental consequences of desalination concentrate disposal have limited the practical adoption of desalination systems for inland brackish water. Desalination concentrate, which is generated by desalination facilities, has the ability to offer water and nutrients for microalgal growth. A useful application for concentrate from desalination systems is required to boost the feasibility of installing desalination procedures for both inland brackish and seawater plants. Several research has been conducted to investigate the use of desalination concentrate as a medium for microalgal culture. This paper reviews the impact of desalination concentrate on microalgal productivity by describing instances of microalgae cultivated in desalination concentrate. Based on the research results, it was found that *Chlorella vulgaris*, *Scendesmus quadricauda*, *S. platensis, Nannochloropsis oculata* and *Dunaliella tertiolecta* can be cultivated on desalination brine. Also, the paper reviews the different applications of these types which may contribute to adding revenue that will reduce the cost of desalinated water.

Keywords Desalination · Brine · Microalgae · Biomass

Introduction

With the increase in human population and water scarcity, the desalination of seawater became the only choice for new water resource. However, desalination operations depend on high power consumption that raises the cost of production to 3–7 times than other water resources (Pistocchi et al. 2020; Dhakal et al. 2022). In recent years, the cultivation of microalgae has been a common trend among several countries as it serves different types of benefits and can be used in different forms. Microalgae can grow in either saline or freshwater under different conditions hence; showing the adaptability of this type of plant-like organism (Sathasivam et al. 2017). Different types of microalgae that can accommodate saline conditions, such as *Chlorella* and *Scenedesmus* are the most reported active types cultivated at high salinities. There are plenty of usages for microalgae such as pond stabilization since they can tolerate high amounts of salts (Rahman et al. 2020; Araújo et al. 2021).

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Growth conditions for microalgae in brine water

The salinity of brine water used to cultivate microalgae ranges from brackish water to high salinity water, and oil content up to 100 ppm (Sahle-Demessie et al. 2019) as presented in Tables 1 and 2. However, there are specific conditions regarding the cultivation of microalgae, comprising the microalgae constant need for aeration and small quantities of nutrients (Sandeep et al. 2013). Aside from the salinity level that varies from different species to another, pH should be at an alkaline level.

There are several species of microalgae that can adapt to reside in highly saline waters which contribute to biomass

Table 1 Growth conditions of different microalgae species in brine water

Growth conditions	Range	References
pH	8.5–9	Sandeep et al. (2013), Sánchez et al. (2015)
Light intensity (Lux)	2500–5000 3500	Sandeep et al. (2013), Kim et al. (2015)
Temperature	29–35 °C	
Total suspended solids (TSS) mg L^{-1}	20–254	Talebi et al. (2016), Ammar et al. (2018)
Dissolved organic carbon (DOC) mg L^{-1}	270–470	Almaraz et al. (2020)

Table 2 Salinity tolerance and production values of different microalgae species in brine water

Genus	Production value	Salinity tolerance (mg L^{-1})	References
Chlorella	Biofuel, nutrient	50,000	Wang et al. (2016), Daliry et al. (2017), Figler et al. (2019)
Scenedesmus	Biofuel, nutrient	45,000–80,000	Figler et al. (2019), El-Sayed et al. (2010)
Nannochloropsis	Biofuel, nutrient	Max. 81,000	Gu et al. (2012), ElBarmelgy et al. (2021)
Dunaliella	Nutrient	35,000–135,000	Oren (2014), Sedjati et al. (2019)

production. One of the main species is the cyanobacterium species such as *Spirulina platensis*, *Spirulina maxima* and *Spirulina argentina* (Sánchez et al. 2015). *Spirulina* or the blue-green microalgae can be cultivated in different types of media including brine medium. It has several benefits and antioxidant factors that can help in human health and can serve as a nutritional factor (Ku et al. 2013; Wells et al. 2017). Mexico is the biggest country that produces *Spirulina* with over 3000 tons per year. WHO announced theat *Spirulina* is known as 'superfood' meaning that it consists of high nutrient levels (Sandeep et al. 2013).

However, several studies investigate salt stress focusing on four types of microalgae species which are *Scenedesmus, Chlorella, Dunaliella* and *Nannochloropsis* (Dolganyuk et al. 2020; Arash et al. 2021 and Udayan et al. 2022). Furthermore, *Scenedesmus* is a type of freshwater microalgae that can adapt to severe marine environments (Gigante 2013). After different studies on *Scenedesmus*; it was found that this genus is successful in adaptation to brine water, in addition, it can highly absorb nitrogen, potassium, calcium, sodium, and phosphorus (El-Sayed et al. 2010; El-Sheekh et al. 2018). *Scenedesmus* is rich in protein and has been seen as a biofuel production tool due to its lipid accumulation capability (Ho et al. 2010; Valdez-Ojeda et al. 2015 and Pushpakumari-Kudahettige et al. 2018). *Scenedesmus* are highly affected by the pH and light intensity, these two factors have a direct relation to the growth of *Scenedesmus* and its mass production. *Scenedesmus* prefers pH of 6.5 as the pH increases the growth rate of the micro microalgae decreases (Fettah et al. 2022; Difusa et al. 2015).

Moreover, *Chlorella* which is a freshwater alga that consists of proteins and B-complex vitamins that can be extracted for medical purposes, adapted to live in saline conditions (Wells et al. 2017). Moreover, *Chlorella* been used to remove the actual nutrients from wastewater (Ismail et al. 2017; Chamberlin et al. 2018; Znad et al. 2018). Znad et al. (2018), experimented nutrient removal capability of *Chlorella* from primary wastewater, secondary wastewater, and petroleum effluent. It was found that *Chlorella* could remove 100 and 82 of macro-nutrients (N and P) in primary wastewater. Matos et al. (2017), cultivated *Chlorella* in different brine concentration levels, while Wang et al. (2016) conclude that *Chlorella* was able to survive in conditions of 50 g L^{-1}.

Dunaliella, another type of microalgae that can withstand high variances of pH, temperature, and salinity (Rodríguez-DeLaNuez et al. 2012; Oren 2014), it is also a common resident in salt works (Oren 2014). Since *Dunaliella* can adapt to different environmental conditions, its effect on nutrient uptake due to salt stress has been presented in a few studies. Moreover, other species like *Stichococcus*, *Dunaliella salina* and *Stephanoptera gracilis* are species that can tolerate high temperatures and saline water (Van and Glaser 2022; Javor 1989). Not only that but microalgae such as *N. pseudostigmata* (UTEX 1249) and *N. conjuncta* (CCAP 254/1), had the highest concentrate tolerance (Hiibel et al. 2015).

Microalgal species respond to different stressors like hypersalinity, for example, D. salina responds to the high osmotic pressure of the hypersaline environment by increasing the production of glycerol. This occurs via starch degradation and shifting the use of carbon flow towards glycerol biosynthesis which acts as an osmotic element. The outcome is the ability of the cells to survive in the hypersaline environment (Sedjati et al. 2019).

Growing microalgae with desalination brine water has many economic and environmental advantages. This system has lower cost, smoother construction, no energy demands and it valorizes a waste product (El Sergany et al. 2014).

Potential of microalgae mass production in desalination brine

Several features and conditions influence microalgae growth and biomass output. Generally, microalgae need both light and nutrients at a certain temperature to grow properly. However, too much light or Oxygen might have a detrimental impact on the development of microalgae, the type of reliance is inextricably linked to the specific microalgae species. Some of them grow well at low temperatures and light intensities, while others require more light. Other considerations, such as the balance between operating parameters (levels of Oxygen and CO_2), pH, and product quality, must be considered while selecting the best species concentration or water consumption.

Different pilot plants were done in open-air under environmental conditions for microalgae cultivation, this type of cultivation consists of storage tanks, aerators, and manual microalgae separator units (El Sergany et al. 2014). Basins are usually used to place different total dissolved solids (TDS) concentrations and apply different concentrations of artificial saline water. For example, *Scenedesmus* microalgae were added with a rate of 0.4 lit/basin/run to treat the saline water for up to 7 retention days (El Sergany et al. 2014). Another study grew *Dunaliella* in a growth chamber with an 18/6 h light/dark cycle at 26/20 °C and 140 μmol m^{-2} s^{-1} light intensity that contained fluorescent and incandescent lamps, within an aquarium where atmospheric air was pumped through a 2-L flask with sterile water (Hiibel et al. 2015). A pilot plant was created for *Scenedesmus* where it was operated under climatic conditions such as temperature, sunlight, and humidity with three storage tanks. Such tanks were divided into three parallel equal parts (El Sergany et al. 2014). Another cultivation medium contains artificial seawater (33 g L^{-1} natural salt) with 2.5 g L^{-1} $NaHCO_3$ that took place in 720 mL glass photobioreactors to cultivate the cyanobacterium *Arthrospira platensis* (Markou et al. 2020).

Spirulina is usually produced by either culture pond or open pond methods, which is a rectangular pond that is opened and exposed to sunlight, this shape and form helps the water to flow in a circulation that prevents any stagnation point (Shimamatsu 2004). While in a large-scale cultivation process, *Spirulina* can be produced in open ponds and open raceways ponds, ponds can be up to 605 m^2 and a volume of 193 m^3. The operating cost per unit area for *Spirulina* production can vary according to the materials used in the construction of ponds, volume, space, and concentrate optimization (Bioeng 2020).

Mass production of *Scenedesmus* takes place using Raceways bioreactor to have suitable conditions for the cultivation and production of this type of microalgae. The Institute for Agricultural and Fisheries Research and Training (IFAPA) in Almería, Spain, is cultivating *Scenedesmus* in raceway bioreactors inside a greenhouse to have full control of the optimization of conditions for mass production. The scale of such a cultivation process can be limited by the feasibility of smart greenhouses, yet *Scenedesmus* can be grown outside in photobioreactors on a large scale to produce biodiesel. The efficiency and growth rate are highly affected by the seasons, the highest growth rates will be found in August, September, and October. Operating cost of such a method is relatively low compared to smart greenhouses, however, its mass production and efficiency is highly dependent on the season and time (Darwish et al. 2015).

Chlorella vulgaris is one of the most used commercial types of microalgae, as it can be cultivated under different conditions. *Chlorella* can be cultivated for mass production in a short time and without control factors. *Chlorella* grows faster in fresh water under sunlight, so the best method for its cultivation is open-air ponds, but different pilot bioreactors were established to cultivate *Chlorella* under salt stress conditions. It turned out that the salt stress condition has repeatedly enhanced some of the fatty acid releases and lipids that are highly valuable (Ali et al. 2020).

Recent applications of cultivating microalgae in desalination brine water

Microalgae production utilizing brine generated by desalination facilities has recently been investigated as presented in Table 3. *Dunaliella salina*, has gained the most attention due to its exceptional environmental adaption, which includes the production of huge amounts of carotenoids and glycerol (Raja et al. 2007 and Giwa et al. 2017). A pilot scale study was carried out to develop *Dunaliella salina* in outdoor ponds using brine with salinity ranging from 40,000 to 80,000 ppm. It resulted in brine salinity reductions ranging from 13 to 63%, depending on brine content, duration in ponds, and changes in climatic conditions (El Sergany et al. 2014).

Uses of the cultivated microalgae

There are multiple uses for cultivated microalgae, such as *Spirulina*, *Dunaliella* spp., in brine water. They can be utilized in the food industry, cosmetics, as well as pharmaceutical industry where specific nutrients exist such as the antioxidant agent, phycocyanin (Sandeep et al. 2013) and β-carotene which is converted to vitamin A which is

Table 3 Recent research trends in cultivating microalgae in desalination brine water

Microalgae	Desalination brine TDS	growth medium	Cultivation system	References
Chlorella vulgaris	67.59 g L^{-1}	BG-11	Photobioreactor	Almutairi et al. (2021)
Nannochloropsis sp.	70 g L^{-1}	Desalination brine based modified f/2 medium	Lab scale 5-L flasks	Elbarmelgy et al. (2021)
Scenedesmus sp.	40–80 g L^{-1}	BG-11	Microalgae Ponds	El Sergany et al. (2014)
Microalgae	18–44 g L^{-1}		Bioreactors	Myint et al. (2015)
C. vulgaris, S. platensis and *N. gaditana*	25–75 g L^{-1}	BBM Paoletti	–	Matos et al. (2017)
Mixed microalgae	Brackish water desalination brine	Anaerobic digested sludges (SADS) and leachates from compost of anaerobic digested sludges (LADS)	Bubbled reactor	Myint et al. (2015)
Scenedesmus quadricauda	8000 mg Cl^{-} L^{-1})	BG-11	Lab scale batch reactor	Maeng et al. (2018)
Spirulina sp. LEB 18	Brackish water desalination brine	Zarrouk medium	Raceway photo bioreactors	Nascimento-Mata et al. (2020)
Nannochloropsis oculata and *Dunaliella tertiolecta*	6.240 g L^{-1}	f/2 medium	Lab scale batch reactor	Shirazi et al. (2018)

essential for human health. *Dunaliella* sp. is highly used in pharmaceutical industries as it has the capacity to produce two main products which are β-carotene and glycerol. Many countries cultivate *Dunaliella* sp. for the use of β-carotene and glycerol such as Australia, Kuwait, Chile, and Spain (Oren 2014). Recent studies proved that *Nannochloropsis* could produce fatty acids and proteins which are essential in food production (Hulatt et al. 2017).

In addition, microalgae are utilized in agricultural production as an organic biofertilizer stimulating the growth of the plants as well as improving the soil properties (Piwowar and Harasym 2020). Moreover, there are several ways in using microalgae in brine aside from using it for agriculture purposes, in which it can be utilized to detoxify minerals and heavy metals (Sánchez et al. 2015). In addition to that, the microalgae can remove calcium and salts from their own growth mediums reducing the overall brine salinity by 20 percent which decreases the environmental impact of brine disposal (Figler et al. 2019).

Furthermore, using microalgae as a source of energy, the biomass could be harvested to produce energy as biofuel. The genus *Nannochloropsis* has gained a strong position in the biofuel research field. Plenty of studies were tested on several strains which can promote lipid production. Additionally, the ability of microalgae to utilize wastewater nutrients and saltwater for growth not only reduces the production costs by replacing the commercial growth medium but also purifies the wastewater for reuse in irrigation and other commercial applications (Sheets et al. 2014; Mitra and Mishra 2019).

Moreover, green microalgae are used for the remediation of industrial wastewater generated from natural gas productions with a TDS level of up to 25,000 ppm and oil content of up to 100 ppm (El Sergany et al. 2014; Ismail 2021). Another potential application of microalgal biomass cultivated in brine would be pigments' production and as animal or fish fodders (El Sergany et al. 2014).

The actual cost of phycocyanin is 0.3 USD per mg which makes it very attractive for businesses to invest in such a component (Sandeep et al. 2013). For example, Chile produces about 30 tons per year of microalgae and the estimated production cost of dried *Spirulina* is 11.4 USD dollars per kg which is highly affordable for businesses (Sánchez et al. 2015).

Conclusion

The environmental consequences of concentrate disposal have limited the practical adoption of desalination systems for inland brackish water, diminishing desalination's capacity to solve worldwide water shortages. A useful application for concentrate from desalination systems is required to boost the feasibility of installing desalination procedures for both inland brackish and seawater. The concept of growing microalgae in the concentrate stream to ease desalination concerns while also satisfying energy demands by supplying feedstock for biofuel production. Based on the research results, five main species can be cultivated on desalination brine. These types include *Chlorella vulgaris*, *Scendesmus quadricauda*, *S. platensis, Nannochloropsis oculata* and *Dunaliella tertiolecta*. They can tolerate brine salinity from 6000 to 80,000 mg L^{-1}. Cultivation of marine microalgal species in brine concentrates from water desalination units might be a potential method of removing contaminants while also creating feedstock for biofuel production.

Acknowledgements The American University in Cairo's Center for Applied Research on the Environment and Sustainability (CARES), School of Science and Engineering, provided funding for this research.

Funding Open Access funding enabled and organized by Projekt DEAL. Not applicable.

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for Publication Not applicable.

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