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Energy usage and carbon dioxide emission saving in desalination by using desalination concentrate and wastes in microalgae production

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ABSTRACT

Energy usage and CO_2 emission between traditional electrodialysis reversal (EDR) and innovative EDR desalinations were compared. The difference between traditional and innovative EDR desalination depended on which concentrate treatment was employed. Traditional EDR desalination consists of electrodialysis as concentrate treatment, while innovative EDR desalination consists of *Dunaliella salina* production as concentrate treatment. Microalgae species *D. salina* and *Arthrospira (Spirulina) platensis* were cultured in used bottles (3.7 L) as reactors and using desalination concentrate and supernatant from anaerobic digested sludge (SADS) as growth medium and nutrients. *D. salina* was grown in reactors D_1, D_2, D_3, and D_4. *Spirulina platensis* was in S_1, S_2, S_3, and S_4. SADS was supplied to reactors D_1, D_2, S_1, and S_2 as nutrient. Bold's Basal Medium was supplied to reactors D_3 and D_4 while F2 was supplied to reactors S_3 and S_4 as nutrient. Conductivity of desalination concentrates used in reactors D_1 and D_3 was 31.8 and in D_2 and D_4 25.4 mS/cm, respectively. Conductivity of concentrate in reactors S_1 and S_3 was 35.9 and in S_2 and S_4 21.5 mS/cm, respectively. Dry weight concentrations of *D. salina* grown in reactors D_1 and D_2 with SADS (1.36–1.49 g/L) were achieved which were more than that with Bold's Basal Medium (0.84–1.04 g/L) in reactors D_3 and D_4. Dry weight concentrations of *S. platensis* with SADS (1.41–1.98 g/L) in reactors S_1 and S_2 were achieved which were more than that supplied with F2 (0.68–1.20 g/L) in reactors S_3 and S_4. In those cases where SADS was the nutrient, low conductivity mediums provided the higher microalgae dry weight concentrations. Dry weights of both species achieved by reusing concentrate and SADS in our studies were 1.49 g/L (*D. Salina*) and 1.98 g/L (*S. platensis*) that are comparable to that of literature data where sea water and pretreated sea water were used. Both species gain a negative net energy ratio. Energy content of 3.02–4.24 kJ/L is required for a positive net energy ratio in microalgae growth culture. Conductivities of growth mediums from all reactors in which *D. salina* were grown are less than the conductivity of drinking water quality required for sheep. Net energy ratio of *D. salina* is less than that of *S. platensis*. For conservative and reusable drinking water for sheep, *D. salina* was used as microalgae to treat concentrate in

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our analyses. Energy usage and CO_2 emission saved from innovative integrated desalination were 4–14%.

Keywords: CO_2 emission saving; Desalination concentrate; *Dunaliella salina*; Energy saving; Net energy ratio; *Spirulina platensis*

1. Introduction

1.1. Further treatment required for desalination concentrate

In the past several years, the western USA has suffered and continues to suffer from severe drought. The water level in rivers has decreased along with the water level of the reservoirs downstream. These losses are typically replaced by pumping and desalting brackish groundwater that carries total dissolved solids (TDS) > 1,000 mg/L. Desalination technologies such as reverse osmosis, nanofiltration, and electrodialysis (reversal) (ED(R)) to desalt brackish groundwater into drinking water show promise, but these technologies have a big drawback when applied in large-scale systems because only dissolved ions are physically transferred from one stream to another stream. The transferred ions carried by the stream have very high conductivity and have not received treatment. The direct and indirect discharges of the concentrate pose an environmental risk, both now and, more so, in the future as such CO_2-untreated discharges build up in the atmosphere little by little which, subsequently, contributes to climate change. The literature repeatedly suggests treating desalination concentrate further. Additional treatment, however, raises the desalination cost, energy usage, and carbon dioxide concentration emission.

1.2. Reuse desalination concentrate in culturing microalgae

Spirulina requires dissolved inorganic carbon as a nutrient for growth. *Spirulina* can consume dissolved carbon dioxide in water medium as a primary substrate for its growth [1]. *Spirulina* is a photosynthesizing *cyanophyte* (blue-green algae) and has the ability to grow energetically in sturdy sunlight under hot temperatures and highly alkaline conditions [2]. *Spirulina* prospers in alkaline lakes where it is difficult or impossible for other organisms to live [1,3]. *Dunaliella* prospers in high-salinity water. In open lakes, microalgae growth cycles are normally limited by the availability of nutrients in the water medium. The growth and carotenogenesis medium cost one-third of the total cost of thorough production of *Dunaliella salina* [4]. If *D. salina* can be cultured from cost-free growth medium and nutrient, not only about one-third of the total cost but also CO_2 emission from fossil-based manufacturing growth medium and nutrients can be avoided.

1.3. Reuse anaerobic digested sludge in microalgae culture for sustainability

Reusing waste materials improves the net energy gain of the first- and second-generation biofuels and will improve the third-generation biofuel. The first-generation biofuels were fed from energy plants (sugar cane, corn, and soybean), but were accompanied by excessive water and land uses and deforestation. The second-generation biofuels were generated from lignocellulose agriculture and forest residues. However, their conversion rates are slow and they need large areas of reactor footprint land and are economically not feasible. To be environmentally friendly and cost-effective, the literature recommended that the whole energy crops traditionally unused and residues from lignocellulose agriculture and forest be co-fed with animal waste and/or anaerobic digested sludge to stoichiometrically balance the carbon, nutrients, and micro-organisms and accelerate the biochemical conversion rate in the first- and second-biofuel processes, respectively. Microalgae were suggested as third-generation biofuels, thus eliminating the disadvantages of the first- and second-generation biofuel processes. Oil from microalgae process was not yet economically viable in 2007 technologies [5] as revealed by both the key projects funded by the governments of the USA and Japan. Algae biodiesel production cost is almost 10-fold higher than crude oil [6]. Literature everywhere, therefore, has concentrated on finding cost-free sources of carbon, nutrients, growth mediums, and reactor materials as much as possible to further reduce the production costs of microalgae [2,7–9] and to increase the sustainability of the environment.

The reuse of desalination concentrate, supernatant from anaerobic digested sludge (SADS), and used bottles in microalgae production follows the fundamental eco-environmental and ecologically sound practices. Conservation environmentalists recommended that the investigation of the fundamentals of eco-environmental and ecologically sound environmental practices be carried out to initialize the regions specific standards or

best practices for achieving the highest harvests with least environmental impact. That means that processes for sustainable energy production must be environmentally benign, reduce greenhouse gas production, and utilize renewable resources. Desalination concentrate, SADS, and used bottles are renewable resources.

1.4. Hypothesis

HCO_3^- acts as a buffer and protects microalgae growth culture from pH fluctuations that can be harmful to microalgae growths. Additionally, HCO_3^-, as an inorganic carbon source, improves growth cultures in carbon storage compared to CO_2 [10]. Concentrate from brackish groundwater desalination dissolves more HCO_3^- than that from sea water desalination. *Spirulina* prospers in high CO_3^{2-} and HCO_3^- water [11]. CO_3^{2-}-, HCO_3^--, and alkaline-rich desalination concentrate with pH (8.5–11.0) is ideally suitable for *Spirulina platensis* growth [1]. *Dunaliella* species are native to salty lake water [12]. *Dunaliella* also has a wide range of pH forbearing ability ranging from pH 1 (*D. acidophila* [13]) to pH 11 (*D. salina*). *D. salina* is one of the most environmentally forbearing eukaryotic organisms recognized and can survive from sea water (= 3% NaCl) to NaCl saturation (= 31% NaCl), and temperature ranging from <0 °C to >38 °C [14,15]. Energy consumed per energy produced for nutrients in microalgae production is 0.455 MJ/MJ [16]. The objectives of this article are: (one) to evaluate the net energy ratio of microalgae (*D. salina* and *Arthrospira (Spirulina) platensis)* production and (two) to analyze the energy usage and CO_2 saved in these microalgae production in used bottles as reactors.

2. Method

2.1. Analytical method and sampling

Microalgae species *D. salina* were sampled in the New Mexico State University Lab. *Arthrospira (Spirulina) platensis* were sampled at the University of Texas at Austin. These species were grown in used bottles (3.785 L volume) by reusing desalination concentrate as the growth medium and SADS from wastewater treatment plant as nutrients (Table 1). To narrow the gap between lab- and field-scale studies, natural desalination concentrate samples were used in the research for all the tests [17]. Desalination concentrate samples were collected from desalination concentrate ponds of the Brackish Groundwater National Desalination Research Facility located in Alamogordo, NM, USA. Anaerobic digested sludge was collected from Las Cruces Wastewater Treatment Plant, NM. Desalination concentrate and anaerobic digested sludge were separately centrifuged for 3 min at 10,000 rpm to collect the supernatants. The supernatants were used in the studies. Dry weight concentration and optical density of growth culture were used to identify the microalgae growth. About 10 mL of cell suspension sample was withdrawn from the reactor, centrifuged for 3 min at 10,000 rpm, the supernatant was decanted, and the remaining microalgae slurries were dried at 103–105 °C in an oven to measure the dry weight concentration of microalgae, and the dry weights concentrations of the microalgae were measured according to SM 2540D [18,19]. The same volume of supernatant of each sample was also dried in the same oven to obtain the correct TDS concentration from microalgae slurries to get TDS-free dry weight concentration of microalgae. The optical density of growth culture was measured with the spectrophotometer (Hach DR/2010) at 560 nm wavelength, the same wavelength 560 nm recommended by Concas et al. [20] for the measurement of optical density. The pH was measured with Cole Parmer pH meter AB15 accumet basic. The conductivity was measured with the Hach sension5 conductivity meter. Dry weight concentrations were measured at 13 and 11 points after 41 and 34 d of treatment for *D. salina* and *S. platensis*, respectively. Optical density of growth culture was measured at 15 and 12 points after 41 and 34 d of treatment for *D. salina* and *S. platensis*, respectively. Conductivity of growth culture was measured at 18 and 12 points after 41 and 34 d of treatment for *D. salina* and *S. platensis*, respectively. Optical density of growth culture was measured at 15 and 12 points after 41 and 34 d of treatment for *D. salina* and *S. platensis*, respectively. The pH of growth culture was measured at 17 and 12 points after 41 and 34 d of treatment for *D. salina* and *S. platensis*, respectively.

2.2. Contents in open reactors

All reactors were filled with desalination concentrate and seed microalgae as shown in Table 1. Reactors D_1, D_2, S_1, and S_2 were fed with SADS as nutrients. Reactors D_3 and D_4 were fed with Bold's Basal Medium [21] and S_3 and S_4 with F2 [22] as nutrients. The reactors were bubbled with air from the environment (which contained CO_2 at 0.0387% by volume), 8 hours a day. All reactors were directly exposed to sunlight from 9:00 am to 5:00 pm on non-holidays by taking the reactors outside during daylight hours and moving them back into the lab room at night. The experiments D_1, D_2, D_3, and D_4 were performed during November–December 2011

Table 1
Contents in reactors

Reactor	Desalination concentrate		Seed microalgae		Seed microalgae	Nutrient
	Conductivity μS/cm	Volume L	Weight g/L dry	Volume L		
D_1	31,800	2.00	0.79	0.11	*D. salina*	SADS
D_2	25,442	2.00	0.79	0.11	*D. salina*	SADS
D_3	31,800	2.00	0.45	0.08	*D. salina*	BBM
D_4	25,442	2.00	0.45	0.08	*D. salina*	BBM
S_1	35,900	1.97	1.01	0.10	*S. platensis*	SADS
S_2	21,500	1.97	1.01	0.10	*S. platensis*	SADS
S_3	35,900	1.97	2.68	0.10	*S. platensis*	F2
S_4	21,500	1.97	2.68	0.10	*S. platensis*	F2

Notes: SADS = Supernatant from anaerobic digested sludge after centrifugation at 10,000 rpm for 3 min twice. BBM = Bold's Basal Medium.

and S_1, S_2, S_3, and S_4 were performed during January–February 2012 in New Mexico State University, Las Cruces, NM. Sunlight radiation data were not collected since sunlight radiation varies with time (from 9:00 am to 5:00 pm) during the day and location of surface in reactors. The reactors were illuminated with light bulbs on holidays when the reactors were in the lab. The radiations from light bulbs to reactors were also not collected since the exposure time of light bulb is negligible compared to the exposure time of sunlight. SADS was fed periodically as fed-batch culture. The seed microalgae concentrations for *D. salina* and *S. platensis* were 0.029 (stdev 0.014) and 0.089 (stdev 0.047) g/L in reactors *D* and *S*, respectively. These different concentrations of seed microalgae between *D. salina* and *S. platensis* affected the growth of these microalgae, differently.

3. Results and discussion

Dry weight concentrations of *D. salina, and S. platensis*, optical density, conductivities of growth media, nutrient added as fed-batch, pH, temperature of cultures when the reactors were in lab, and air flow rate vs. culturing time are plotted in Figs. 1 and 2. The temperature of the cultures was 32.8–47.2˚C when the reactors were outside the lab directly under the sun. The volume of the nutrient added to reactors increases with the time of experimentation as shown in Figs. 1(d) and 2(d) because the microalgae's dry weight concentrations and optical density of growth medium increase with time as shown in Figs. 1(a) and (b), and 2(a) and (b). The comparison of dry weight concentrations and specific growth rates of *D. salina* and *S. platensis* between our studies and literature data is presented in Tables 3 and 4.

3.1. Comparison of biomass microalgae between SADS and BBM or F2

Dry weight concentrations of *D. salina* supplied with SADS (1.36–1.49 g/L) were higher than that supplied with BBM (0.84–1.04 g/L) as shown in Fig. 1(a). Dry weight concentrations of *S. platensis* supplied with SADS (1.41–1.98 g/L) were higher than that supplied with F2 (0.68–1.20 g/L) as shown in Fig. 2(a). The reason for this may be that the micro-organism grew in SADS [23] along with microalgae, and the micro-organism promoted microalgae growth. This finding agrees with the finding of Wang et al. [24]. Wang et al. [24] stated that the specific growth rate of microalgae from concentrate (wastewater from sludge centrifuge) is higher than that from wastewater before and after primary settling and aeration tank. Wastewater from sludge centrifuge has more micro-organisms than the wastewater before and after primary settling and aeration tank. In cases of SADS as nutrients, low conductivity mediums provide higher microalgae dry weight concentrations. In cases of Bold's Basal Medium and F2 as nutrients, higher conductivity mediums provided higher microalgae dry weight concentrations.

3.2. Comparison of biomass microalgae between our study and literature

Dry weight concentrations of both species by reusing concentrate and SADS achieved from our studies are 1.49 g/L (*D. Salina:* Fig. 1(a)) and 1.98 g/L (*S. Platensis:* Fig. 2(a)). These results are comparable to that of literature data (*D. salina* 1.06 g/L and *S. platensis* 0.8–2.99 g/L in Tables 3 and 4), where sea water and pretreated sea water were used. Dry weight

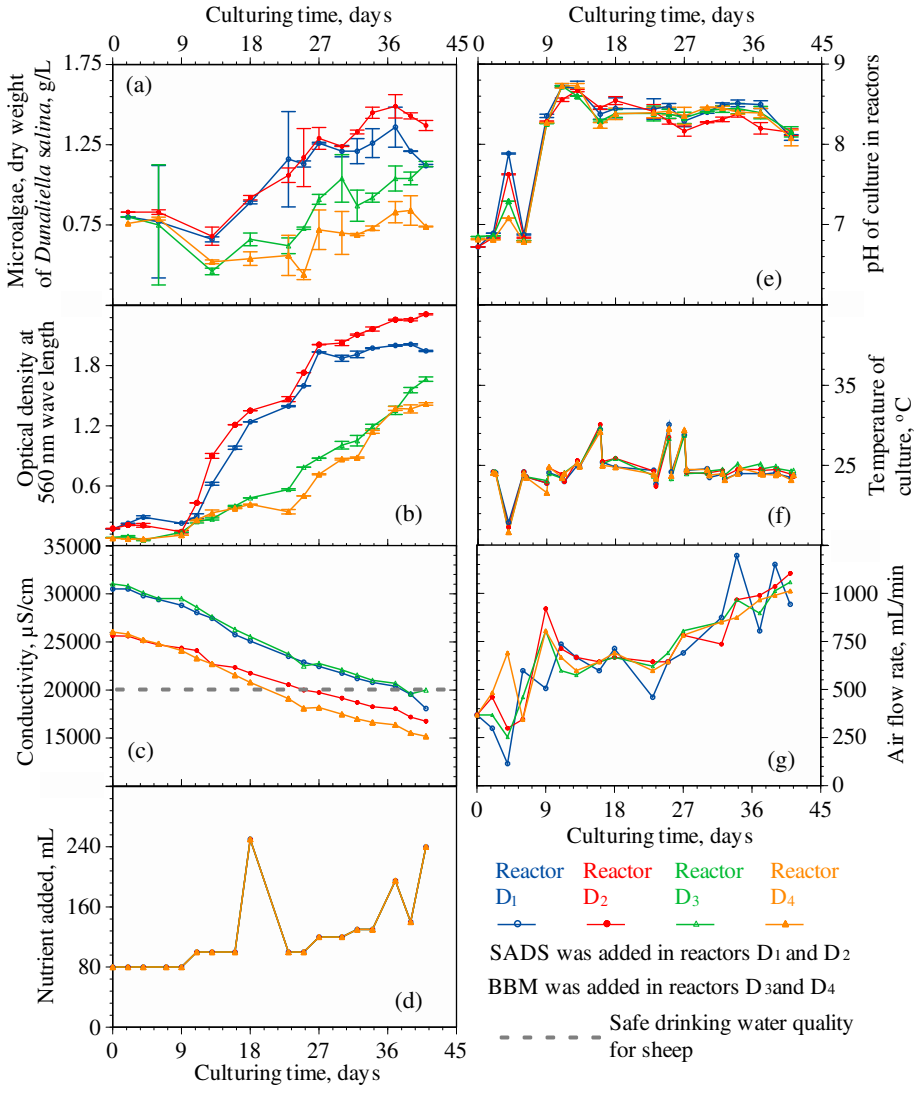

Fig. 1. *D. salina*'s growing characteristics with culturing time: (a) dry weight; (b) optical density; (c) conductivities of media in reactors; (d) nutrient added into reactors; (e) pH; (f) temperature when reactors were in the lab; (g) air flow rate.

concentration 2.587 g/L of *S. platensis* was observed in the work of Volkmann et al. [25] in desalinated wastewater. Dry weight concentration of 2.37 g/L of dry biomass was observed by Pandey et al. [26] at pH 8.25, temperature at 30°C, and light intensity of 3 Klux [27]. Dry weight concentration of *S. platensis* 2.34 g/L was found on the 27th day of culturing in 30% petha waste medium supplemented with standard medium (for example, CFTRI medium) in triplicate at 3 Klux light intensity, pH 9.5 ± 0.1, and 30°C ± 2 temperature under 12/12 h light/dark cycles [27]. Dry weight concentration 2.91 g/L of *S. platensis* was observed at input CO_2 concentration of 10% on the 25th day of culturing by Ramanan et al. [28]. Longer culturing time 37–39 d for *D. salina* was required to reach maximal growth due to higher conductivities in concentrate (Table 2) and color from SADS. The color of SADS decreases the transparency of the used plastic bottles as reactors. The growth rate of microalgae also depends on the amount of seed microalgae in the growth media [29,30].

The growth of *D. salina* may be inhibited in desalination concentrate by brackish groundwater since this concentrate contains high concentration of SO_4^{2-} and high concentration of HCO_3^-. *D. salina* prefers high pH of 11 while the pH of the growth culture was between

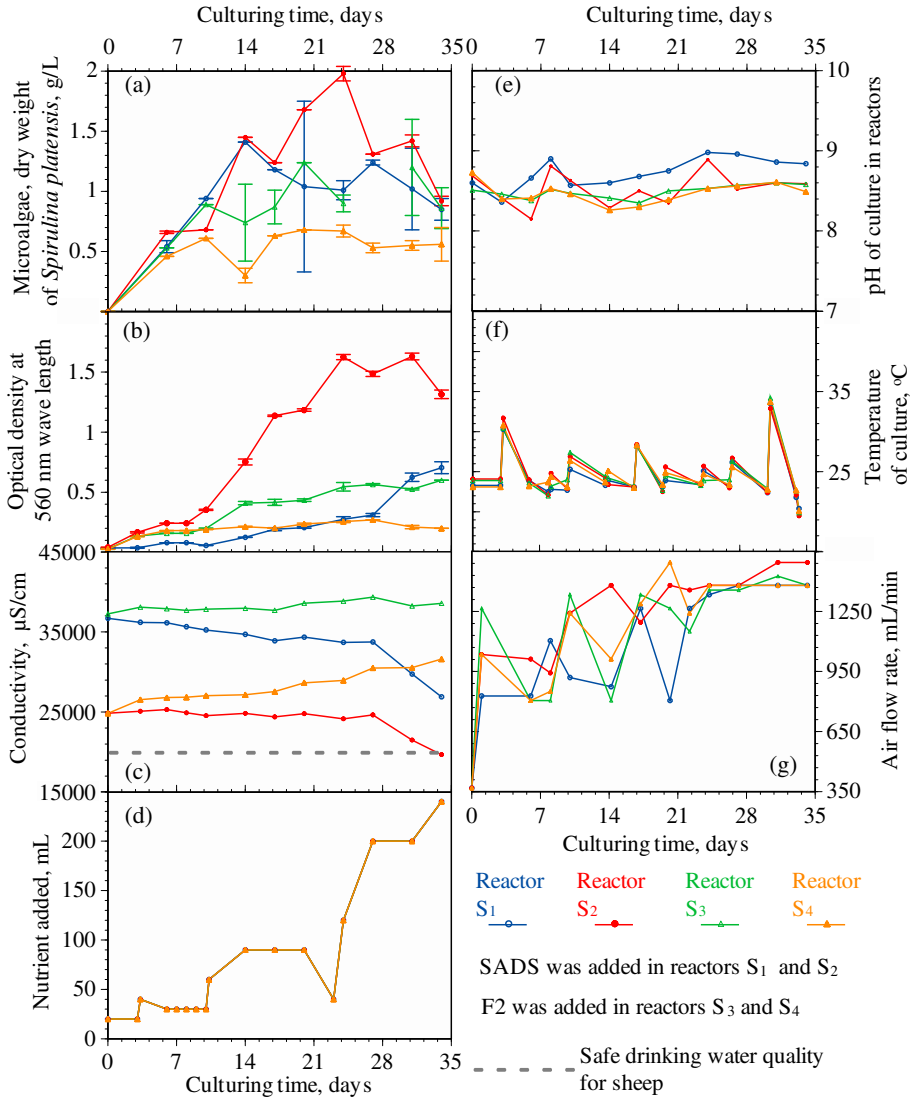

Fig. 2. *S. platensis*'s growing characteristics with culturing time: (a) dry weight; (b) optical density; (c) conductivities of media in reactors; (d) nutrient added into reactors; (e) pH; (f) temperature when reactors were in the lab; (g) air flow rate.

6.8 and 8.8 in Fig. 1(e). Therefore, longer culturing time is required for *D. salina* to reach the maximum dry weight concentration compared to *S. platensis*, since *Spirulina* prospers in high CO_3^{2-} and HCO_3^- water [11] in the pH range of 8.5–11.0 [1].

3.3. Specific growth rate

$$\mu = \{\mathrm{Ln}(\mathrm{Wy}/\mathrm{Wx})\}/\{\mathrm{ty} - \mathrm{tx}\} \quad (1)$$

where Wy and Wx are the microalgae dry weight (W) at the start (tx) and the end (ty) of the logarithmic growth phase [31,32].

The specific growth rate was found from the Eq. (1). The available specific growth rates of *D. salina* from literature, culturing with NaCl as growth medium [33], and manufactured chemical nutrient [34] were used to compare with that from our studies. The natural desalination concentrate and SADS were used in our studies (Tables 3 and 4), and the specific growth rates from our studies (0.095–0.114 for *D. salina* in Table 3 and 0.019–0.034 for *S. platensis* in Table 4) were lower than those reported in literature (0.12–0.47 for *D. salina* [34] in Table 3 and 0.255 for *S. platensis* from [51] in Table 4), where sea water and pretreated sea water were used as water medium in

Table 2
Maximal dry weight concentrations in reactors

Reactor	Seed microalgae	Nutrient	At which the highest dry weight occurs				
			Weight g/L dry	Optical density	pH	Temp ℃	*d*
D_1	*D. salina*	SADS	1.36	2.002	8.5	24–24	37
D_2	*D. salina*	SADS	1.49	2.259	8.2	24–24	37
D_3	*D. salina*	BBM	1.04	1.355	8.4	24–25	37
D_4	*D. salina*	BBM	0.84	1.369	8.2	23–24	39
S_1	*S. platensis*	SADS	1.41	0.125	8.6	23–24	14
S_2	*S. platensis*	SADS	1.98	1.625	8.9	23–26	24
S_3	*S. platensis*	F2	1.24	0.434	8.5	23–24	20
S_4	*S. platensis*	F2	0.68	0.236	8.4	23–25	20

Note: SADS = Supernatant from anaerobic digested sludge after centrifugation at 10,000 rpm for 3 min twice.

closed reactor. Misleading conclusions can be made in comparison in the microalgae growth rate in between different water mediums, different nutrient supplied, and different types and characteristics of reactors used [30]. Pittman et al. [30] states that nutrient removal rates are comparable. However, microalgae growth rates are higher in artificial wastewater than that in natural wastewater [29,35]. This may be due to the increased toxicity of natural wastewaters, or the competitive effects of indigenous bacteria and protozoa, or by the diverse chemical composition of the natural wastewaters [30]. Natural concentrate from desalination of the evaporation pond has to be used for simulating real-world conditions [17] and to reduce the disconnection gap between lab and field. Sheehan et al. [36] stated that there is disengagement between the lab and the field. The lab condition requires simulating the field situation as such using natural concentrate in the experiments.

The lower specific growth rates of microalgae may also be due to the temperature fluctuation between daytime (open outdoor 32.8–47.2℃ in our study) and nighttime (in lab 17–30℃ in our study), or the illumination problems from the color of SADS (optical density 0.58 at 560 nm wavelength). The higher concentrations of TDS, N, Mg^{2+}, and Ca^{2+} can be toxic to the microalgae growth [37]. Tredici and Zittelli [38] found that the outdoor cultures of *S. platensis* (1.09 and 1.26 g/L/d) were lower than that of indoor (1.64–1.93 g/L/d). However, the enthalpies are similar (20.9–21.6 kJ/g). Torzillo et al. [39] concluded that temperature and light irradiance influence the biomass composition and found that dry weight concentrations of biomass were reduced during the night due to the decrease of these two factors.

3.4. Waste materials improve the net energy gain in microalgae production

The energy produced per energy consumed in microalgae processes is in the range of 0.2–2 MJ/MJ [16,40] without reusing waste materials. The analyses of net energy ratio are shown in Table 5. The maximal dry weights of *D. salina* and *S. platensis* grown in desalination concentrate and supplied with SADS are 1.36–1.49 and 1.41–1.98 g/L, respectively, in our study. The lipid contents of *D. salina* and *S. platensis* are in the ranges of 3.29–4.03 and 6.2–10.6% [41–43]. Analyses show that both species gain negative net energy ratio reusing of waste materials (reactor, growth medium, and nutrients) were reused. Energy consumed per energy produced for nutrients in microalgae production is 0.455 MJ/MJ [16], and energy saved from nutrients is about 45.5% of the energy produced.

3.5. Net energy ratio

Net energy ratio was reported in Table 5. Net energy ratio was calculated as energy produced divided by energy used in microalgae process. Energy produced and energy used were calculated by Eqs. (2) and (3) as:

$$\text{Energy produced} = (\text{DW}_{\text{microalgae}})\quad(\text{Lipid}_{\text{content}})\quad(\text{Energy}_{\text{content}})\quad(\eta) \tag{2}$$

where energy produced = energy production from microalgae (dry) grown in 1 L culture, $kJ/L_{culture}$; $DW_{microalgae}$ = microalgae (dry) concentration grown in 1 L growth culture, $g/L_{culture}$; $Lipid_{content}$ = lipid content in respective microalgae (dry), %; $Energy_{content}$ = energy content in lipid, kJ/g ; and η = efficiency of microalgal oil to biodiesel, %.

Table 3
Comparison of dry weight and specific growth rate betwith our data and literature values for *D. salina*

D. salina data from our lab					*D. salina* data from literature						
Water media	Nutrient	Dry weight, g/L	Culturing time day	Specific growth rate, d^{-1}	Water media	Nutrient	Dry weight, g/L	Culturing time day	Specific growth rate, d^{-1}	Type of reactor	Ref.
Conc.[a]	SADS	1.36	37	0.095	Sea water	$NaNO_3$	1.06	17			[50]
Conc.[b]	SADS	1.49	37	0.097	Sea water	F2	0.33	Semi-cont.	0.12–0.33	Open	[34]
Conc.[a]	BBM	1.04	37	0.114	Sea water	F3	0.53	25, bench	0.33	Open	[34]
Conc.[b]	BBM	0.84	39	0.106	Sea water	F4	1.65	Semi-cont.	0.22–0.46	Closed	[34]
					Sea water	F5	2.00	25, bench	0.47	Closed	[34]
					10% NaCl	J/1			0.28		[33]

Notes: Conc.[a] = desalination concentrate which has conductivity 31,800 μS/cm; Conc.[b] = desalination concentrate which has conductivity 25,442 μS/cm. SADS = Supernatant from anaerobic digested sludge after centrifugation at 10,000 rpm for 3 min twice. BBM = Bold's basal medium.

Table 4
Comparison of dry weight and specific growth rate between our data and literature values for *Spirulina platensis*

S. platensis data in our lab					*S. platensis* literature data					
Water media	Nutrient	Dry weight, g/L	Process day	Specific growth rate, d^{-1}	Water media or reactor	Nutrient medium	Dry weight, g/L	Process day	Specific growth rate, d^{-1}	Ref.
Conc.[a]	SADS	1.41	14	0.030	PS		2.26–2.99	25	0.255	[51]
Conc.[a]	SADS	1.98	24	0.032	OP	Zarrouk's	1.1	8		[52]
Conc.[a]	F2	1.20	31	0.034	DW	50%ADE	1.23	14		[53]
Conc.[a]	F2	0.68	24	0.019	10% OM	Zarrouk's	0.8–1.0	21–25		[54]
					CP	NO_3^-, HCO_3^{2-}	1.70	NA		[43]
					Desalinated WW		2.59	NA		[25]
							2.37	NA		[26,27]
					30% petha	CFTRI	2.34	27		[27]
							2.91	25		[28]

Notes: Conc.[a] = desalination concentrate which has conductivity 35,900 μS/cm. Conc.[b] = desalination concentrate which has conductivity 21,500 μS/cm. ADE = anaerobically digested distillery effluent. OM = olive oil mill wastewater; NaOCl was used to decrease the phenol concentration and turbidity. PS = pretreated sea water. OP = open pond 2.5 m^2. DW = distilled water. CP = closed photobioreactor. CFTRI = prescribed medium [27]. SADS = supernatant from anaerobic digested sludge after centrifugation at 10,000 rpm for 3 min twice.

Table 5
Net energy analysis of microalgae production

Description/reactors	*D. salina*		*S. platensis*		Unit	Ref.
	D_1	D_2	S_1	S_2		
Energy produced from microalgae production						
Dry weight of microalgae from our study	1.36	1.49	1.41	1.98	$g/L_{culture}$	
Lipid content in respective dry microalgae	3.29	3.29	10.6	10.6	%	[41,42]
Lipid content in respective dry microalgae	4.03	4.03	6.2	6.2	%	[41,43]
Energy content in lipid	38.3	38.3	38.3	38.3	kJ//g	[57]
Energy conversable from microalgae	1.91	2.09	4.54	6.37	$kJ/L_{culture}$	
Efficiency, algal oil to biodiesel	63.9	63.9	63.9	63.9	%	[55]
Energy produced	1.22	1.33	2.90	4.07	$kJ/L_{culture}$	
Energy used in microalgae production						
Energy used in supplying CO_2 from air	0.35	0.35	0.35	0.35	$kWh/kg_{biomass}$	
Energy used in pumping for harvesting	0.10	0.10	0.10	0.10	$kWh/kg_{biomass}$	[56]
Energy for centrifugation for harvesting	0.10	0.10	0.10	0.10	$kWh/kg_{biomass}$	[56]
Energy for oil extraction and conversion to biodiesel	0.05	0.05	0.05	0.05	$kWh/kg_{biomass}$	[56]
Total energy used	0.60	0.60	0.60	0.60	$kWh/kg_{biomass}$	[56]
Total energy used	0.60	0.60	0.60	0.60	$Wh/g_{biomass}$	
Total energy used	0.82	0.89	0.85	1.19	$Wh/L_{culture}$	
Total energy used	2.91	3.19	3.02	4.24	$kJ/L_{culture}$	
Net energy ratio						
Energy produced/energy used	0.42	0.42	0.96	0.96	Unit less	
Energy loss in microalgae production	−1.70	−1.86	−0.12	−0.17	$kJ/L_{culture}$	

$$E_{used} = E_{CO_2} + E_{pumping} + E_{centrifuging} + E_{extraction} \quad (3)$$

E_{used} = energy used in microalgae production, E_{CO_2} = energy used in supplying CO_2 from air, $kJ/L_{culture}$; $E_{pumping}$ = energy used in pumping in microalgae harvesting process, $kJ/L_{culture}$; $E_{centrifuging}$ = energy used for centrifugation in microalgae harvesting process, $kJ/L_{culture}$; $E_{extraction}$ = energy used for oil extraction, and conversion to biodiesel, $kJ/L_{culture}$.

The net energy ratios calculated from *D. salina* and *S. platnesis* were 0.42 and 0.96, respectively, as shown in Table 5, and these values are less than neutral. The net energy ratios of *D. salina* are less than those of *S. platnesis* because *D. salina* had both less dry weight concentration and less lipid content compared to the *S. platnesis*. Net energy ratio from *S. platnesis* (0.96) is close to neutral. From Table 4, 3.02–4.24 kJ/L of the energy content in microalgae growth culture is required for a positive net energy ratio.

3.6. Using waste concentrate in microalgae (D. salina) production for desalination energy reduction

Conductivities of growth mediums at the end of test from all reactors in which *D. salina* were grown are less than 20,000 μS/cm, which is the maximal allowable conductivity of drinking water quality required for sheep as shown in Fig. 1(c). Net energy ratio of *D. salina* is less than that of *S. platensis*. For conservative and reusable drinking water for sheep, *D. salina* was used as microalgae to treat concentrate in our analyses.

Tables 6 and 7 compare energy consumption in desalinations between traditional EDR desalination with ED as concentrate treatment and innovative integrated desalination with microalgae production as concentrate treatment. Traditional EDR desalination contains two processes as shown in Fig. 3(a). The first process is the EDR desalination, and the data from [45,46] were used in the analyses as shown in Tables 6 and 7. The second process is concentrate treatment, in which the concentrate (TDS 0.2–2%) from the first stage was concentrated to TDS 12–20% using ED with energy consumption of 1–7 kWh/m^3 [47–49]. The innovative integrated desalination also contains two processes as shown in Fig. 3(b). The first process is the same as that of the traditional EDR desalination. However, concentrate from the first process was used in microalgae production as concentrate treatment in innovative desalination.

Table 6
Traditional vs. innovative EDR desalination: feed TDS 1817 mg/L

1	2	3	4	5	6	7	8	9	10	11
First stage-EDR desalination			Second stage-conc. management			Second stage-conc. management				
Feed dissolved ions 1,817 mg/L			Traditional EDR desalination			Microalgae production using conc.				
Water recovery rate % [45]	Power used in desalination kJ/L *p* [45]	Power used in pumping kJ/L *p*	Power used in concentrate management kJ/L *c* [46–48]	kJ/L *p*	Life cycle desalination power used kJ/L *p*	Power loss in algae kJ/L *c**	Power loss in algae kJ/L *p*	Life cycle desalination power used kJ/L *p*	Power usage saving %	Saving in CO_2 emission %
70.9	1.90	0.38	2.94	1.21	3.49	1.78	0.73	3.01	13.7	13.7
79.3	2.18	0.44	3.06	0.80	3.41	1.78	0.46	3.08	9.8	9.8
82.8	2.37	0.47	3.53	0.73	3.58	1.78	0.37	3.21	10.2	10.2
85.7	2.64	0.53	3.79	0.63	3.80	1.78	0.30	3.47	8.8	8.8
88.1	2.91	0.58	4.24	0.57	4.06	1.78	0.24	3.73	8.1	8.1
87.4	2.92	0.58	3.96	0.57	4.07	1.78	0.26	3.76	7.7	7.7
79.2	3.16	0.63	4.33	1.14	4.92	1.78	0.47	4.26	13.6	13.6
86.0	3.10	0.62	4.96	0.81	4.53	1.78	0.29	4.01	11.4	11.4
86.0	3.81	0.76	5.72	0.93	5.50	1.78	0.29	4.86	11.7	11.7

Notes: *c* = conc. = concentrate waste, *p* = product. EDR – electrodialysis reversal. Traditional EDR desalination – EDR as first stage for desalination and EDR as second stage for concentrate treatment. Innovative EDR desalination – EDR as first stage for desalination; microalgae as second stage for concentrate treatment. *Referred from the average value of data from columns 2 and 3 of Table 5.

Table 7
Traditional vs. innovative EDR desalination: feed TDS 4,042 mg/L

1	2	3	4	5	6	7	8	9	10	11
First stage-EDR desalination			Second stage-conc. management			Second stage-conc. management				
Feed dissolved ions 1,817 mg/L			Traditional EDR desalination			Microalgae production using conc.				
			Power used in concentrate management							
Water recovery rate % [44]	Power used in desalination kJ/L *p* [44]	Power used in pumping kJ/L *p*	kJ/L *c* [46–48]	kJ/L *p*	Life cycle desalination power used kJ/L *p*	Power loss in algae kJ/L *c**	Power loss in algae kJ/L *p*	Life cycle desalination power used kJ/L *p*	Power usage saving %	Saving in CO_2 emission %
73.2	6.5	1.30	4.19	1.53	9.35	1.78	0.65	8.47	9.4	9.4
79.4	6.8	1.37	4.71	1.22	9.43	1.78	0.46	8.67	8.1	8.1
84.0	7.1	1.42	5.50	1.05	9.56	1.78	0.34	8.85	7.4	7.4
86.8	7.7	1.54	6.17	0.94	10.18	1.78	0.27	9.52	6.5	6.5
91.4	8.9	1.77	8.31	0.78	11.41	1.78	0.17	10.79	5.4	5.4
93.1	11.6	2.33	9.83	0.73	14.68	1.78	0.13	14.09	4.1	4.1

Notes: *c* = conc. = concentrate waste, *p* = product. EDR – electrodialysis reversal. Traditional EDR desalination – EDR as first stage for desalination and EDR as second stage for concentrate treatment. Innovative EDR desalination – EDR as first stage for desalination; microalgae as second stage for concentrate treatment. *Referred from the average value of data from columns 2 and 3 of Table 5.

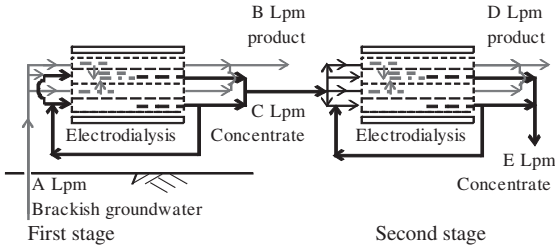

Fig. 3(a). Traditional ED desalination and concentrate management, first stage: traditional ED desalination; second stage: concentrate management in which concentrate from the first stage was fed in the microalgae production; Lpm = litre per minute.

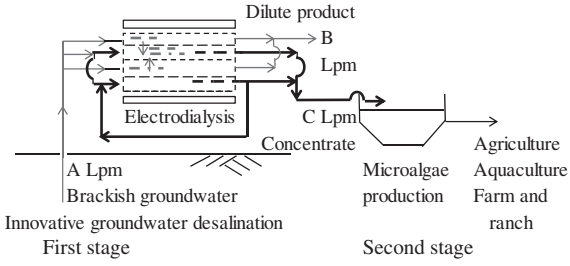

Fig. 3(b). Innovative ED desalination and concentrate management, first stage: traditional ED desalination; second stage: concentrate management in which concentrate from the first stage was fed in the microalgae production; Lpm = litre per minute.

Energy consumption of EDR desalination is 0.528–3.23 kWh/m^3 (1901–11,628 J/L as shown in Tables 6 and 7) of desalted product water, depending on water recovery rate and chemical characteristics of feed water [45,46]. The pumping energy was assumed as 20% of energy consumption of EDR desalination as shown in our analysis in Tables 6 and 7.

Data in columns 1, 2, and 3 of Tables 6 and 7 were for first-stage EDR desalination which desalted brackish groundwater into drinking water. Data in columns 1 and 2 of Table 6 were referred from [46]. Data in columns 1 and 2 of Table 7 were referred from [45]. Data in column 3 of Tables 6 and 7 were calculated from 20% of column 2. Data in columns 4, 5, and 6 of Tables 6 and 7 were for second-stage traditional EDR desalination which desalted concentrate from the first stage into drinking water and highly concentrated concentrate. Data in column 4 of Tables 6 and 7 were referred, interpolated, and extrapolated from literature data that stated that TDS 0.2–2% from the first stage was concentrated to TDS 12–20% by using ED with the energy consumption of 1–7 kWh/m^3 [47–49]. Data in column 5 of Tables 6 and 7 were converted to kWh per m^3 of product from kWh per m^3 of concentrate. Data from column 6 of Tables 6 and 7 were summed from data from columns 2, 3, and 5. Data in columns 7, 8, and 9 of Tables 6 and 7 were for second-stage concentrate management using concentrate from first stage in microalgae production. Data in column 7 of Tables 6 and 7 were calculated from the difference in the energy content of *D. salina* and the energy used as shown in Table 5. Data in column 8 were kWh per m^3 of concentrate as shown in column 7 of Tables 6 and 7 into kWh per m^3 of product. Data in column 9 of Tables 6 and 7 were the sum of Data columns 2, 3, and 8. Data in column 10 of Tables 6 and 7 were calculated by employing data from columns 6 and 9. CO_2 emissions in column 11 of Tables 6 and 7 were calculated from life cycle CO_2 emission rate 1.001 kg/KW-hr.

Our calculations show that minimal energy usage and CO_2 emission reduction employing innovative integrated EDR desalination are 4–14% as shown in Tables 6 and 7.

The desirable TDS and maximum TDS for drinking water quality guidelines for sheep are 5,000–10,000 mg/L TDS or 10,000–20,000 μS/cm. The range for beef cattle is 4,000–5,000 mg/L TDS or 8,000–10,000 μS/cm according to NSW Public Works [44]. The conductivities from reactors D_1, D_2, D_3, and D_4 after 39, 27, 39, and 23 d of *D. salina* treatment were lower than the conductivity requirement in the drinking water quality guidelines for sheep, respectively, as shown in Fig. 1(c). The conductivities from reactors S_2 after 34 d of *S. platensis* treatment were lower than the conductivity requirement in the drinking water quality guidelines for sheep as shown in Fig. 2(c). The treated desalination concentrate contains green food, protein, nutrients, minerals, and desalted water; the treated desalination concentrate from reactors D_1 to D_4 and S_2 can be given to sheep in semi-arid regions where green food and water resources are gradually diminishing.

4. Conclusion

The maximal dry weights of *D. salina* and *S. platensis* grown in desalination concentrate and supplied with SADS (1.36–1.49 g/L) were more than that supplied with BBM and F2 due to micro-organism growth along with microalgae. Micro-organism promotes

microalgae growth. The maximal dry weight concentrations of *D. salina* and *S. platensis* grown in desalination concentrate and supplied with SADS were comparable to that in the literature. Energy usage and CO_2 emission reduction employing innovative integrated EDR desalination with microalgae production as concentrate treatment are 4–14% lower than concentrate treatment using ED.

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References

[1] M.A.B. Habib, M. Parvin, T.C. Huntington, M.R. Hasan, A Review on Culture, Production and Use of Spirulina as Food for Humans and Feeds for Domestic Animals and Fish, FAO Fisheries and Aquaculture Circular. No. 1034, FAO, Rome, 2008, p. 33.

[2] J.A.V. Costa, L.M. Colla, P.F.D. Filho, Improving *Spirulina platensis* biomass yield using a fed-batch process, Bioresour. Technol. 92 (2004) 237–241.

[3] E. Kebede, G. Ahlgren, Optimum growth conditions and light utilization efficiency of *Spirulina platensis* (= *Arthrospira fusiformis*) (Cyanophyta) from Lake Chitu, Ethiop. Hydrob. 332 (1996) 99–109.

[4] C.A. Santos, A.M. Vieira, H.L. Fernandes, J.A. Empis, J.M. Novais, Optimisation of the biological treatment of hypersaline wastewater from *Dunaliella salina* carotenogenesis, J. Chem. Technol. Biotechnol. 76 (2001) 1147–1153.

[5] M.E. Huntley, D.G. Redalje, CO_2 mitigation and renewable oil from photosynthetic microbes: A new appraisal, Mitig. Adapt. Strat. Global Change 12 (2007) 573–608.

[6] Y. Chisti, Biodiesel from microalgae beats bioethanol, Trends Biotechnol. 26 (2008) 126–131.

[7] E.J. Olguın, E. Alarcon, S. Galicia, Recycling of pig waste recovery of *Spirulina* sp. at pilot plant level, under tropical conditions, in: Proceedings of the Eighth International Conference on Applied Algology, September 29–October 1, 1999, Montecatini Terme, Italy.

[8] G. Samorì, C. Samorì, F. Guerrini, R. Pistocchi, Growth and nitrogen removal capacity of Desmodesmus communis and of a natural microalgae consortium in a batch culture system in view of urban wastewater treatment: Part I, Water Res. 47 (2013) 791–801.

[9] F.G. Acién, J.M. Fernández, J.J. Magán, Production cost of a real microalgae production plant and strategies to reduce it, Biotechnol. Adv. 30 (2012) 1344–1353.

[10] R.D. Gardner, E. Lohman, R. Gerlach, Comparison of CO_2 and bicarbonate as inorganic carbon sources for triacylglycerol and starch accumulation in Chlamydomonas reinhardtii, Biotechnol. Bioeng. 110 (2013) 87–96.

[11] A. Richmond, Handbook of Microalgal Mass Culture. CRC Press, Boston, MA, 1990.

[12] M.A. Borowitzka, The mass culture of *Dunaliella salina*. FAO Corporate Document repository, Murdoch: Murdoch University, 1990. http://www.fao.org/docrep/field/003/AB728E/AB728E00.htm (accessed January 18, 2013).

[13] H. Gimmler, U. Weis, C. Weis, H. Kugel, B.D. Treffny, Dunaliella acidophila (Kalina) Masyuk? An alga with a positive membrane potential, New Phytol. 113 (1989) 175–184.

[14] M. Ginzburg, Dunaliella: A green alga adapted to salt, Adv. Bot. Res. 14 (1987) 93–183.

[15] L.J. Borowitzka, M.A. Borowitzka, β-carotene (Provitamin A) production with algae, in: E.J. Vandamme (Ed.), Biotechnology of Vitamins, Pigments and Growth Factors, Elsevier Applied Science, London, 1989, pp. 15–26.

[16] D.L. Sills, V. Paramita, M.J. Franke, M.C. Johnson, T.M. Akabas, C.H. Greene, J.W. Tester, Quantitative uncertainty analysis of life cycle assessment for algal biofuel production, Environ. Sci. Technol. 47 (2013) 687–694.

[17] C. Visvanathan, B.D. Marsono, B. Basu, Removal of THMP by nanofiltration: Effects of interference parameters, Water Res. 32 (1998) 3527–3538.

[18] APHA, Standard Methods for the Examination of Water & Wastewater, American Public Health Association, Washington, DC, 2005.

[19] J.M. Valigore, P.A. Gostomski, D.G. Wareham, A.D. O'Sullivan, Effects of hydraulic and solids retention times on productivity and settleability of microbial (microalgal-bacterial) biomass grown on primary treated wastewater as a biofuel feedstock, Water Res. 46 (2012) 2957–2964.

[20] A. Concas, L. Pisu, G. Cao, Mathematical modelling of Chlorella vulgaris growth in semi-batch photobioreactors fed with pure CO_2, Chem. Eng. Trans. 32 (2013) 1021–1026.

[21] H.W. Nichols, H.C. Bold, *Trichosarcina polymorpha* gen. et sp. Nov, J. Phycol. 1 (1965) 34–38.

[22] R.R.L. Guillard, J.H. Ryther, Studies of marine planktonic diatoms: I. Cyclotella nana Hustedt, and Detonula confervacea (Cleve) gran, Can. J. Microbiol. 8 (1962) 229–239.

[23] M. Myint, A. Ghassemi, N. Nirmalakhandan, Review of nondestructed anaerobic digested sludge to reinstate concentrate from electrodialysis reversal desalination in bioenergy production, Environ. Eng. Sci. 27 (2010) 811–823.

[24] L. Wang, M. Min, Y. Li, P. Chen, Y. Chen, Y. Liu, Y. Wang, R. Ruan, Cultivation of green algae *Chlorella* sp. in different wastewaters from municipal wastewater treatment plant, Appl. Biochem. Biotechnol. 162 (2010) 1174–1186.

[25] H. Volkmann, U. Imianovsky, J.L.B. Oliveira, E.S.S. Anna, Cultivation of *Arthrospira* (*spirulina*) *platensis* in desalinator wastewater and salinated synthetic medium: Protein content and amino-acid profile, Braz. J. Microbiol. 39 (2008) 98–101.

[26] J.P. Pandey, A. Tiwari, Optimization of biomass production of *Spirulina maxima*, J. Algal Biomass Utln. 1 (2010) 20–32.
[27] S. Jain, S. Masih, S.G. Singh, Potentiality of petha (*benincasa hispida*) waste for the growth of *spirulina platensis*, Res. J. Agric. Sci. 2 (2011) 133–135.
[28] R. Ramanan, K. Kannan, A. Deshkar, R. Yadav, Enhanced algal CO_2 sequestration through calcite deposition by *Chlorella* sp. and *Spirulina platensis* in a mini-raceway pond, Bioresour. Technol. 101 (2010) 2616–2622.
[29] P.S. Lau, N.F.Y. Tam, Y.S. Wong, Effect of algal density on nutrient removal from primary settled wastewater, Environ. Pollut. 89 (1995) 59–66.
[30] J.K. Pittman, A.P. Dean, O. Osundeko, The potential of sustainable algal biofuel production using wastewater resources, Bioresour. Technol. 102 (2011) 17–25.
[31] A.M. Wood, R.C. Everroad, L.M. Wingard, Chapter 18: Measuring growth rates in microalgal cultures, in: R.A. Andersen (Ed.), Algal Culturing Techniques, Elsevier Academic Press, Burlington, MA, 2005, pp. 269–285.
[32] R. Huerlimann, R. de Nys, K. Heimann, Growth, lipid content, productivity, and fatty acid composition of tropical microalgae for scale-up production, Biotechnol. Bioeng. 107 (2010) 245–257.
[33] F. García, Y. Freile-Pelegrín, D. Robledo, Physiological characterization of *Dunaliella* sp. (Chlorophyta, Volvocales) from Yucatan, Mexico, Bioresour. Technol. 98 (2007) 1359–1365.
[34] A. Prieto, J.P. Cañavate, M. García-González, Assessment of carotenoid production by *Dunaliella salina* in different culture systems and operation regimes, J. Biotechnol. 151 (2011) 180–185.
[35] A. Ruiz-Marin, L.G. Mendoza-Espinosa, T. Stephenson, Growth and nutrient removal in free and immobilized green algae in batch and semi-continuous cultures treating real wastewater, Bioresour. Technol. 101 (2010) 58–64.
[36] J. Sheehan, T. Dunahay, J. Benemann, P. Roessler, A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae, U.S. Department of Energy's Office of Fuels Development. National Renewable Energy Laboratory, Midwest Research Institute, Golden, CO, 1998, Contract No. DE-AC36-83CH10093.
[37] H.W. Kim, R. Vannela, B.E. Rittmann, Responses of *Synechocystis* sp. PCC 6803 to total dissolved solids in long-term continuous operation of a photobioreactor, Bioresour. Technol. 128 (2013) 378–384.
[38] M.R. Tredici, G.C. Zittelli, Efficiency of sunlight utilization: Tubular versus flat photobioreactors, Biotechnol. Bioeng. 57 (1998) 187–197.
[39] G. Torzillo, A. Sacchi, R. Materassi, Temperature as an important factor affecting productivity and night biomass loss in *Spirulina platensis* grown outdoors in tubular photobioreactors, Bioresour. Technol. 38 (1991) 95–100.
[40] L. Batan, J. Quinn, B. Willson, T. Bradley, Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae, Environ. Sci. Technol. 44 (2010) 7975–7980.
[41] C.D. Tanzi, M.A. Vian, F. Chemat, New procedure for extraction of algal lipids from wet biomass: A green clean and scalable process, Bioresour. Technol. 134 (2013) 271–275.
[42] Z.-Y. Li, S.-Y. Guo, L. Li, Bioeffects of selenite on the growth of *Spirulina platensis* and its biotransformation, Bioresour. Technol. 89 (2003) 171–176.
[43] G. Markou, I. Chatzipavlidis, D. Georgakakis, Cultivation of *Arthrospira* (*Spirulina*) *platensis* in olive-oilmill-wastewater treated with sodium hypochlorite, Water Res. 112 (2012) 234–241.
[44] NSW Public Works, Brackish Groundwater: A Viable Community Water Supply Option? The National Water Commission, Australian Government, Canberra, 2011.
[45] D. Elyanow, R.G. Parent, J.R. Mahoney, Parametric tests of an electrodialysis reversal. (EDR) system with aliphatic anion membranes, Desalination 38 (1981) 549–565.
[46] D. Elyanow, E. Sieveka, J. Mahoney, The determination of super-saturation limits in an EDR unit with aliphatic anion membranes, in: Nineth Annual Conference and International Trade Fair of the National Water Supply Improvement Association, Washington, DC, Vol. II, May 31–June 4, 1981.
[47] E. Korngold, L. Aronov, N. Belayev, K. Kock, Electrodialysis with brine solutions oversaturated with calcium sulfate, Desalination 172 (2005) 63–75.
[48] E. Korngold, L. Aronov, N. Daltrophe, Electrodialysis of brine solutions discharged from an RO plant, Desalination 242 (2009) 215–227.
[49] A. Pérez-González, A.M. Urtiaga, R. Ibáñez, I. Ortiz, State of the art and review on the treatment technologies of water reverse osmosis concentrates, Water Res. 46 (2012) 267–283.
[50] W.-W. Huang, B.-Z. Dong, Z.-P. Cai, S.-S. Duan, Growth effects on mixed culture of *Dunaliella salina* and Phaeodactylum tricornutum under different inoculation densities and nitrogen concentrations, Afr. J. Biotechnol. 10 (2011) 13164–13174.
[51] J.T. Leema, R. Kirubagaran, N.V. Vinithkumar, P.S. Dheenan, S. Karthikayulu, High value pigment production from *Arthrospira* (*Spirulina*) *platensis* cultured in seawater, Bioresour. Technol. 101 (2010) 9221–9227.
[52] A.A. Gitelson, S. Laorawat, G.P. Keydan, A. Vonshak, Optical properties of dense algal cultures outdoors and their application to remote estimation of biomass and pigment concentration in *Spirulina platensis* (Cyanobacteria), J. Phycol. 31 (1995) 828–834.
[53] R. Kaushik, R. Prasanna, H.C. Joshi, Utilization of anaerobically digested distillery effluent for the production of *Spirulina platensis* (ARM 730), J. Sci. Ind. Res. 65 (2006) 521–525.
[54] C.C. Reichert, C.O. Reinehr, A.V. Costa, Semicontinuous cultivation of the Cyanobacterium *Spirulina platensis* in a closed photobioreactor, Braz. J. Chem. Eng. 23 (2006) 23–28.
[55] S. Chinnasamy, A. Bhatnagar, R.W. Hunt, Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications, Bioresour. Technol. 101 (2010) 3097–3105.
[56] D.E. Brune, T.J. Lundquist, J.R. Benemann, Microalgal biomass for greenhouse gas reductions: Potential for replacement of fossil fuels and animal feeds, J. Environ. Eng. 135 (2009) 1136–1144.
[57] L. Lardon, A. Hélias, B. Sialve, Life-cycle assessment of biodiesel production from microalgae, Environ. Sci. Technol. 43 (2009) 6475–6481.