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Techno-economics of algae production in the Arabian Peninsula

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HIGHLIGHTS

- Modeling of algae biomass production costs and productivities in the Arabian Gulf.
- Raceway ponds and flat panel reactors most feasible option for regional production.
- Lowest biomass production costs of 2.9 €·kg^{-1} found for open raceway ponds.
- Scale-up from 1 to 10 ha has most impact on cost reductions.
- Increased photosynthetic efficiency and temperature optima reduce costs up to 42.5%

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ABSTRACT

The Arabian Peninsula's advantageous climate, availability of non-arable land, access to seawater and CO_2-rich flue gas, make it an attractive location for microalgae biomass production. Despite these promising aspects, the region has seen very few studies into the commercial feasibility of algae-based value chains. This work aims to address this gap through a techno-economic feasibility study of algae biomass production costs, comparing different photobioreactor types, locations, and production scales. Flat panel and raceway pond cultivation systems were found to be the most economically attractive cultivation systems, with biomass production costs as low as 2.9 €·kg^{-1}. Potential cost reductions of up to 42.5% and 25% could be accomplished with improvements in photosynthetic efficiencies and increased culture temperatures, respectively. As of such, efforts to source local thermo- and photo- tolerant strains could be the key to unlock the potential of the region for algae commercialization, linking into food, feed and nutraceutical industries.

1. Introduction

The drive towards feedstocks with improved ecological and sustainable footprints for fuels, feed, food and chemicals has been increasing steadily over the past decades. Microalgae - microscopic plant-like organisms which perform photosynthesis and produce a plethora of different commercially interesting metabolites - have caught the interest of many researchers, both in academic and industrial contexts, as one such potential sustainable feedstock (Mathimani and Pugazhendhi, 2019). Despite the increasing interest into algae commercialization, the majority of algal developments remain at research scale (Borowitzka and Vonshak, 2017; da Silva and Reis, 2015). This has been, in part, attributed to the limited available knowledge on scale-up costs factors and the improvement requirements for strain selection, cultivation systems, and harvesting mechanisms (Khan et al., 2018). In order to establish a successful global algae-based industry, more insight is needed into the techno-economics of algae production, and more specifically, which processes most significantly impact scalability and cost reductions. This will enable researchers, developers, and investors to make the right decisions regarding algae R&D, scale-up and commercialization.

High biomass productivity (and related photosynthetic efficiencies), is one of the areas in which significant advances can be made to decrease the production costs (Banerjee and Ramaswamy, 2019; Tredici, 2010). Large regions in the Middle East and North Africa have been identified to be able to support the highest global theoretical biomass productivities of up to 200–240 t·ha^{-1}·y^{-1}, due to their climatic conditions and light availability. Such productivities have however not yet been

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Table 1
Climate data inputs used for the study, data is average ± stdev of annual data.

Parameter	Unit	Kuwait	Oman		Qatar	Saudi Arabia		UAE	Ref
		Nuwaiseeb	*Al Hadd*	*Salalah*	*Al Khor*	*Al Wajh*	*Jizan*	*Sharjah*	
Annual global average solar radiation[a]	$Wh \cdot m^{-2}$	6217	5719	5309	6138	5881	6360	6258	Climate. OneBuilding
Dry Bulb Temperature (air) [a]	°C	26.5 ± 9.3	25.6 ± 3.1	26 ± 2.1	26.4 ± 7.0	26.1 ± 4.6	30.9 ± 3.5	28.3 ± 7.3	
Relative Humidity[a]	%	36 ± 14.7	72.5 ± 11.4	73.8 ± 14.2	58.3 ± 15.7	64.9 ± 9.7	65.9 ± 7.3	55.3 ± 15.6	
Dew Point Temperature[a]	°C	7.2 ± 3.9	19.8 ± 3.7	20.4 ± 4.3	16.1 ± 4.5	18.5 ± 5.8	23.6 ± 1.8	17.1 ± 4.1	
Wind Speed[a]	$m \cdot s^{-1}$	3.6 ± 0.9	5.2 ± 1.5	2.2 ± 0.7	4.1 ± 1.3	4.0 ± 1.9	3.1 ± 1.8	3.1 ± 1.3	
Seawater Temperature[b]	°C	24.9 ± 6.0	27.2 ± 2.1	26.5 ± 1.6	26.9 ± 5.3	26.8 ± 2.4	30.2 ± 1.9	28.0 ± 4.3	Sea water temperature (2020)

Note: [a] annual average of hourly data over 2004–2018.
Note: [b] annual average of monthly temperatures over 2009–2019

demonstrated for long-term cultivation under outdoor conditions (Tredici, 2010). Furthermore, applied cultivation systems have also been shown to be a key factor influencing both biomass productivities as well as and associated production costs (Carvalho et al., 2006; de Vree et al., 2015; Wang et al., 2012). Closed systems, such as flat panels and tubular reactors, have been demonstrated to result in higher photosynthetic efficiencies and subsequent areal productivities compared to open raceway ponds. Such higher productivities however do come at a cost, as construction and operation of closed systems carries a higher CAPEX and OPEX footprint than open cultivation systems do (Carvalho et al., 2006; de Vree et al., 2015; Ugwu et al., 2008). Lastly, the benefits of closed systems are not equal for all locations. In hot desert- and tropical climates, increased construction and operation costs for required cooling systems do not always balance out the positives of increased productivities in overall financial assessments (Endres et al., 2016; Nwoba et al., 2019).

The Arabian Peninsula, and more specifically the Gulf Cooperation Council (GCC) countries, presents a geographical location with a tantalizing value proposition for large-scale algae production. The region offers an advantageous climate allowing for year-round production, availability of large areas of non-arable land, direct local access to seawater, and a high number of CO_2-rich flue gas point sources. Despite these promising aspects, the GCC region has seen very few studies into feasibility of local algae commercialization. Published studies related to the region are generally limited to strain identification and isolation, and small-scale investigation into high-value secondary metabolites or biofuels (Das et al., 2019a, 2015, 2016; Kitto and Reginald, 2011). Additionally, some studies have investigated the cultivation of halotolerant species (Abu-Rezq et al., 2010; Das et al., 2019a; Harethi and Hernandez, 2014; Kitto and Reginald, 2011), and a small number of strains have been cultivated in semi-large-scale outdoor cultivation systems (Das et al., 2019a, 2015, 2016). All in all, the current breadth of research and development of algal technologies focusing on the GCC region holds significant as-of-yet unexplored potential. This objective of this study is therefore to investigate and compare the techno-economics of algae production across various locations in the GCC (Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (UAE)). The impact of cultivation system (raceway ponds, horizontal tubular, vertical stacked tubular and flat panel), and process design choices on production costs are investigated in order to provide a tool for strategic planning and evaluating the techno-economic viability of an algae-based value-chain in the GCC.

2. Materials and methods

The techno-economic model for biomass production utilized in this study has been developed and is described in detail by Ruiz et al., 2016. The model is based on available empirical information and literature and allows for projections of different scenarios for algae production in various locations. The model relies on (location dependent) inputs such as climate data, productivities, equipment and consumable costs, as well as social- and utilities related costs such as labor, taxes, and electricity. Alterations to the original model are described here.

2.1. Locations and climatology

Seven locations across the GCC were included in the study: Kuwait (Nuwaiseeb), Oman (Hadd and Salalah), Qatar (Al Khor), Saudi Arabia (Al Wajh and Jizan) and United Arab Emirates (UAE, Sharjah). The locations were selected based on their proximity to the coast for sea-water access, spatial distribution and to ensure all GCC countries were covered (with the exception of Bahrain). The locations were chosen as such to provide an accurate representation of the differences which can be expected across the Arabian Peninsula. Bahrain was excluded due to its close proximity to Qatar, and minimal differences in climate. Various location-dependent parameters were included in the study: climate data and seawater temperatures (Table 1), salaries (Table 3), and energy costs (Table 4).

2.2. Production process considerations

The model simulates the defined algae biomass production process, starting from nutrient enrichment of seawater and sterilization through to algae cultivation and biomass harvesting. Harvesting through centrifugation is assumed (base-case), with a 15% (w/w) algal slurry as the end-product of the simulated production process. Furthermore, different scales of cultivation were simulated, ranging from 1 to 100 ha. In all cases, 10% of the cultivation area was assumed to be required to produce inoculum (non-productive area). The total facility size was assumed to be 120% of the cultivation area, with the additional 20% of land required for auxiliary systems such as (office) buildings, roads, and major equipment. It was assumed that the land costs were 1200 $€ \cdot ha^{-1} \cdot yr^{-1}$ (rented basis).

2.3. Production systems

Four cultivation systems were taken into consideration, the designs of which are based on the AlgaePARC pilot facility (Wageningen, the Netherlands) and have been described in detail by Ruiz et al., 2016. A brief description of each system is provided:

- **Horizontal tubular photobioreactor (HT)**; closed system consisting of transparent low-density polyethylene tubes (Ø 0.057 m), placed on the ground at 0.05 m distance, connected by loops at the end of each tube, with a volume:ground ratio of 23.8 $L \cdot m^{-2}$. It was assumed that culture is circulated through the tubes at a liquid

Table 2
Experimental data used in the study; obtained from outdoor cultivation trials at Qatar University's Algal Technologies Program.

Strain	Period	Days *d*	Volume *m³*	Cultivation Mode	Dilution *d⁻¹*	Average Productivity[a] *g·m⁻²·d⁻¹*	PFD *mol·m⁻²·d⁻¹*	PE *%*	Ref.
Tetraselmis sp.	May-2018	30	0.2	R Batch[b]	0.12–0.25	20.77	55.70	1.72%	Das et al. (2019a)
	Jan-2018	31	0.2	R Batch[b]	0.12–0.25	12.97	31.01	1.93%	Das et al. (2019a)
Picochlorum sp.	Oct-2018	8	25	Batch	–	17.25	41.52	1.91%	Das et al. (2019b)
Chrococcidiopsis sp.	Oct-Dec 2016	60	0.2	R Batch[b]	0.25	16.08	33.28	2.23%	Das et al. (2018)
Geitlerinema sp.	May-2019	7	0.2	Batch	–	23.62	56.63	1.92%	Unpublished
Leptolyngbya sp.	Aug-2020	7	0.2	Batch	–	20.56	52.92	1.79%	Schipper et al. (2021)
Average								1.92%	

Note: [a] Average areal biomass productivity over the duration of the cultivation trial.
Note: [b] Repeated Batch.

velocity of 0.45 $m{\cdot}s^{-1}$, and passed through a degasser (separate vessel) for the removal of excess oxygen. Tube length is dependent on oxygen buildup, with the maximum dissolved oxygen content prior to the degasser set at 300% of oxygen saturation.

- **Vertical stacked horizontal tubular photobioreactor (VT)**; closed system consisting of transparent borosilicate glass tubes (Ø 0.065 m), stacked parallel to the ground in a vertical structure (0.95 m high). Each unit containing loops of 8 vertically stacked tubes, with a distance of 0.50 m between each unit, and a volume:ground ratio of 47 $L{\cdot}m^{-2}$. The circulation liquid velocity of the culture was equivalent to the horizontal tubular system, and the length of the tubes was determined based on oxygen buildup, taking into consideration the same process constraints as for the horizontal tubular photobioreactor system.
- **Flat panel photobioreactor (FP)**; closed system consisting of transparent polyethylene 'bags', supported by a steel mesh casing, with a height of 0.50 m, and a light path of 0.02 m, each panel placed 0.25 m apart (volume:ground ratio 37 $L{\cdot}m^{-2}$). Culture mixing is provided through air sparging from the bottom, which also prevents the buildup of excess oxygen, at a flow of 0.32 vvm. The entire front surface area is assumed to be exposed to direct radiation, and diffuse and reflected light can reach the back surface.
- **Raceway pond (RW)**; open system consisting of a shallow pond (0.20 m depth) with a single recirculation loop, and a total volume of 2856 m^3 (width: 28 m, length: 510 m), and a volume:ground ratio of 200 $L{\cdot}m^{-2}$. A single paddlewheel provides mixing and culture circulation at a liquid velocity of 0.25 $m{\cdot}s^{-1}$. A carbonation sump (1.0 m deep and 0.65 m long) across the width of one channel is assumed, to promote carbon transfer to the liquid of pH-dosed CO_2.

2.4. Biomass productivity & operating conditions

The model utilizes photosynthetic efficiencies as the main determining factor for biomass productivities. In Ruiz et al. (2016), these productivities are based on empirical data from AlgaePARC (Wageningen University, the Netherlands), where different reactor types were evaluated side-by-side. The same photosynthetic efficiencies were assumed and applied for the same reactor types in different geographical locations. In the present study it was recognized that local productivities should be applied to improve the accuracy of the model. Empirical data of (semi)large-scale outdoor cultivation in the GCC region is limited, especially for closed photobioreactors. There are, however, a number of cultivation studies in open raceway ponds, located in Qatar. The photosynthetic efficiency of these different experiments was calculated using equation (1):

$$PE = \frac{P_{X,areal} \cdot \Delta H_C^0 \cdot 10^{-3}}{\left(\frac{I_{day}/E_{PAR}}{0.43}\right)} \quad (1)$$

In which PE is the photosynthetic efficiency (% sunlight), $P_{X,areal}$ is the average areal productivity in $g_X{\cdot}m^{-2}{\cdot}d^{-1}$, ΔH_C^0 is the enthalpy of biomass combustions (22.5 $KJ{\cdot}g^{-1}$), I_{day} is the average areal daily photon flux density (mol photons$\cdot m^{-2}{\cdot}d^{-1}$), $E_{PAR}$is the energetic content of the PAR fraction of sunlight (4.76 $mol{\cdot}J^{-1}$), and 0.43 the conversion factor from sunlight to PAR light ($J{\cdot}J^{-1}$) (de Vree et al., 2015).

The average photosynthetic efficiency obtained for the local studies in open raceway ponds, consisting of cultivation of a number of different strains in different seasons, was 1.92% (Table 2). This value was adopted in the model for the photosynthetic efficiency of cultivation in open raceway ponds for the different locations studied. For horizontal tubular, vertical stacked horizontal tubular and flat panel photobioreactors, photosynthetic efficiencies of 1.5%, 2.4% and 2.7% were applied, respectively, as per de Vree et al. (2015), as no empirical regional data was available. Chemostat operation of the cultivation systems was assumed, with 0.16, 0.25, 0.27 and 0.27 d^{-1} dilution rates set for the raceway pond, horizontal tubular, vertical stacked tubular and flat panel photobioreactors, respectively. Lastly, a 300 $d{\cdot}yr^{-1}$ (7200 $h{\cdot}yr^{-1}$) operational uptime was assumed for the facility.

2.5. Nutrients

Urea and triple superphosphate were assumed as nitrogen and phosphate sources, respectively. To minimize the effect of price fluctuations, average prices over 2015–2020 were used: 205 €$\cdot ton^{-1}$ for urea and 272 €$\cdot ton^{-1}$ for triple superphosphate. For CO_2, commercial grade was assumed (base-case), at a price of 184 €$\cdot ton^{-1}$ (Norsker et al., 2011).

2.6. Temperature control

The culture temperature was simulated, considering factors of irradiance, radiation and convection. For the raceway pond, the effects of evaporation and condensation on culture temperature were also simulated, and no temperature control was assumed. For the closed cultivation systems, the maximum culture temperature was set to 40 °C, above which seawater cooling was applied to maintain the same. As the Arabian Gulf is not very deep, and ambient air temperatures fluctuate significantly over the course of a year, seawater temperatures fluctuate strongly as well (Nandkeolyar et al., 2013). Thus, contrary to Ruiz et al. (2016) who assumed fixed water temperatures, a monthly fluctuating seawater temperature was assumed for each location (Table 1). The simulation assumed that cooling occurred through culture submerged heat-exchangers with an efficiency of 75%. The costs of the heat exchangers were based on the same considerations as Ruiz et al. (2016).

2.7. Costs

Simulations were conducted incorporating the costs of resources (utilities, materials, and labor), and equipment. Fluctuations in currency conversion rates were accounted for; all prices were added in their original currency, and conversion to the desired end-currency (EUR) considered the average conversion rates over the year of the quotation (in the case of CAPEX). For OPEX, such as labor and electricity costs, the average conversion rates over 2019 were used (fxtop).

Table 3
Labor cost considerations for different facility sizes and locations.

Facility Size	Plant Manager *FTE*	Supervisor *FTE*	Operator *FTE*	Total *FTE*
1 ha	1	1	8	10
10 ha	1	2	15	18
100 ha	1	3	28	32
Location	**Plant Manager** *Cost·month^{-1}*	**Supervisor** *Cost·month^{-1}*	**Operator** *Cost·month^{-1}*	**Employer's contribution**
Kuwait	KWD 2,070	KWD 1,200	KWD 680	21.0%
Oman	OMR 2,990	OMR 1,920	OMR 870	18.0%
Qatar	QAR 25,600	QAR 14,400	QAR 7,720	17.0%
Saudi Arabia	SAR 26,900	SAR 14,400	SAR 8,520	20.5%
UAE	AED 32,800	AED 17,600	AED 10,500	22.0%

Table 4
Subsidized electricity tariffs for agricultural consumers, for each location.

Location	Electricity Cost·kWh^{-1} [i]		Ref
Kuwait (Nuwaiseeb)	KWD 0.010	€ 0.029	Kuwait News Agency KUNA (2017)
Oman (Hadd)	OMR 0.010	€ 0.023	Authority for Public Service Regulation (Oman) (2017)
Oman (Salalah)	OMR 0.020	€ 0.046	Authority for Public Service Regulation (Oman)
Qatar (Al Khor)	QAR 0.070	€ 0.017	Kahramaa, Qatar General Electric & Water Corporation
Saudi Arabia (all locations)	SAR 0.160	€ 0.038	King Abdullah Petroleum Studies and Research Center
UAE (Sharjah)	AED 0.075	€ 0.018	King Abdullah Petroleum Studies and Research Center (2018)

Note: [i] Conversion to EURO using average conversion rate over 2019.

2.8. Major equipment

The costs and electricity requirements for major equipment units of various capacities were incorporated into the model (pumps, centrifuge, tanks etc.). The ultimate capacity of each unit was based on the calculated maximum capacity requirement during the highest irradiation period of the year (thus highest productivity). For each unit, a maximum of 90% load was assumed and, where required, multiple smaller units were specified until the cost of a larger unit was equal or less in comparison. Prices of major equipment were corrected for inflation, and a 5% purchase tax was applied (International Trade Administration).

2.9. Labor

Total labor cost estimates were based on number of personnel, salary, and employer's contribution. The required number of personnel of a 1 ha facility formed the base-case, consisting of a total of 10 employees (1 plant manager, 1 supervisor, and 8 operators of different skill levels). For scale-up, a non-linear relation between labor requirements and size was assumed, according to the 0.25 power of the capacity ratio (Peters et al., 2003). Salaries were based on average salaries in each country, for Operations Manager, Supervisor, and Process Operator in the engineering sector (Salary Explorer, n.d.). Employer's contributions were added to the labor costs to cover for liability of work-related accidents and occupations illness (SAP) (Table 3).

2.10. Electricity

All GCC countries provide subsidized electricity costs for agricultural activities – these subsidized rates were used for each location, and can be found in Table 4.

Table 5
Comparison of reference and improvement scenarios, applied to 100 ha cultivation scenario located in Qatar (Al Khor).

Parameter	Reactor System	Reference Scenario	Optimized Scenario
Photosynthetic efficiency	RW	1.92%	3.84%
	HT	1.50%	3.00%
	VT	2.40%	4.80%
	FP	2.70%	5.40%
Temperature Optima	RW,HT,VT, FP	40 °C	60 °C
Harvesting	RW,HT,VT, FP	Centrifugation	Vibrating screen & filter press
Operational Days	RW,HT,VT, FP	300 d	333 d
Alternative Urea Source	RW,HT,VT, FP	205 €·t^{-1}	50 €·t^{-1}
Recovered CO_2	RW,HT,VT, FP	0.184 €·kg^{-1}	0.029 €·kg^{-1}
Wastewater treatment costs	RW,HT,VT, FP	0.43 €·m^{-3}	0.215 €·m^{-3}

2.11. Optimization: Sensitivity analsysis

A sensitivity analysis was performed to determine the impact of variation in different parameters on the predicted biomass production costs for a production process based in Qatar (Al Khor). Seven dimensions were analyzed: 1) increased photosynthetic efficiency, 2) increased temperature optimum, 3) alternative harvesting methods, 4) increased operational days, 5) use of waste urea, 6) use of recovered CO_2, and 7) reduced wastewater treatment costs. The aspect of production scale was investigated as an independent case.

For the analysis, the photosynthetic efficiencies were doubled for the different reactor types, whereas temperature optima were chosen as such to eliminate the need for cooling in all cultivation systems. The alternative harvesting method (tilted screen and vacuum filter belt) was selected as it is a common method for the harvesting of larger (filamentous) cyanobacteria such as *Arthrosprira* sp. and *Leptolyngbya* sp. (Vonshak and Richmond, 1988), which could be suitable candidates for production in the region (Schipper et al., 2021, 2020). The increase in operational days assumed chemical engineering industry standard operating days (8000 h·y^{-1}) (Coulson et al., 1991). Costs for waste urea and flue-gas CO_2 were estimates of transport costs only, assuming no purchase costs. Wastewater treatment costs were optimized through a 50% reduction of the base-case, which could be either due to the implementation of water recycling options, or due to a decrease in the volumetric treatment costs (Ruiz et al., 2016). An overview of the optimized scenarios vs. the reference scenarios is given in Table 5.

3. Results and discussion

3.1. Biomass productivities & costs

Algae biomass productivity predictions were made for various cultivation systems and locations across the GCC (Fig. 1 A). The impact of different locations on the projected productivities was minor, which was attributed to similar climates across the region. Significant productivity differences were projected however for the different cultivation systems. Flat panel photobioreactors had the highest potential productivities, ranging from 62 to 74 t·ha^{-1}·yr^{-1} across the different locations, followed by vertical stacked tubular reactors and raceway ponds. Lowest productivities (34–41 t·ha^{-1}·yr^{-1}) were predicted for the horizontal tubular system. The predicted productivities are promising compared to other global productivity predictions made, such as by Tredici et al., 2016, who estimated annual biomass productivities of 36 and 54 t·ha^{-1}·yr^{-1} for flat panel photobioreactors operated in Italy and Tunisia, respectively.

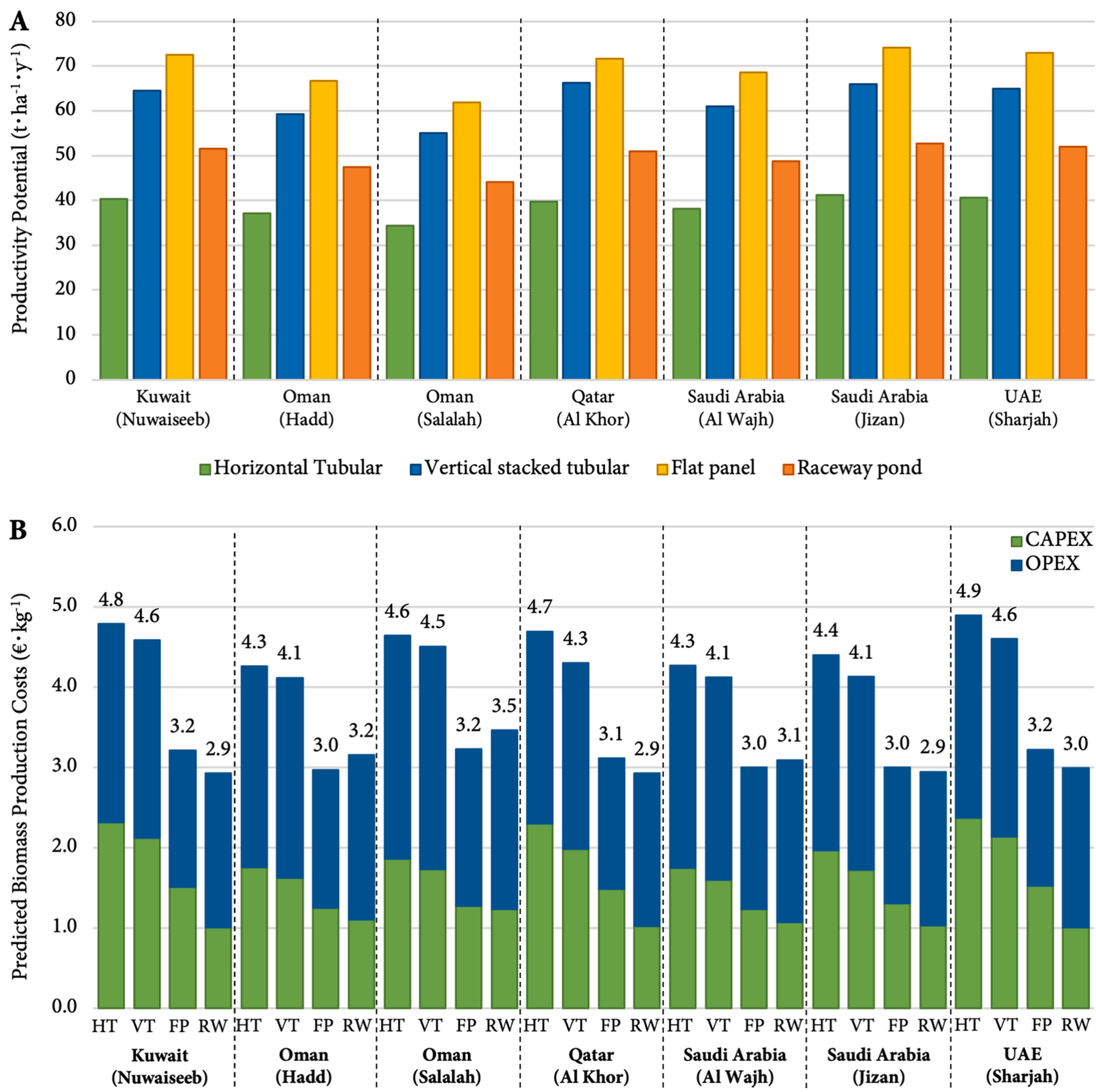

Fig. 1. Projected biomass productivities in t·ha^{-1}·y^{-1} (**A**) and biomass production costs for both CAPEX and OPEX in €·kg^{-1} (**B**), for 100 ha facility in different GCC locations, and four bioreactor types (HT: Horizontal tubular, VT: Vertical stacked tubular, FP: Flat panel, RW: Raceway pond).

Biomass productivity variations across different cultivation systems were mainly attributed to the assumed photosynthetic efficiencies as well as reactor configuration (volume:surface ratio). The photosynthetic efficiency is governed by a multitude of factors, such as strain, cultivation system, and cultivation conditions (light, temperature etc.) and can also be reduced by sub-optimal cultivation conditions (Nwoba et al., 2019). Theoretical maximum photosynthetic efficiency values for outdoor cultivation range from 8 to 12%. Such efficiencies have, however, yet to be demonstrated from actual long-term outdoor cultivation operations (Nwoba et al., 2019; Tredici, 2010). In order to make robust predictions about productivities and associated production costs, empirical data for selected strains, locations, and cultivation systems is essential. For cultivation in raceway ponds, this data is available for the region (Table 2). For other cultivation systems however, values applied are estimations based on results from AlgaePARC in the Netherlands, with *Nannochloropsis* sp. (Ruiz et al., 2016). Remarkably, the photosynthetic efficiencies found for cultivation of various strains over multiple seasons in raceway ponds in Qatar are higher (1.92%) than both those reported for *Nannochloropsis* sp. in the Netherlands (1.2%), as well as average the value of 1.5% generally assumed in literature (Kumar et al., 2015). If this trend can be extrapolated to the other cultivation systems as well, the current predictions could underestimate the biomass production potential of the region.

In terms of predicted biomass production costs (Fig. 1 B), reactor type remains the main determining factor, with minimal variations between the different locations. Both tubular systems had the highest overall cost (4.3–4.9 and 4.1–4.6 €·kg^{-1} for horizontal tubular and vertical stacked tubular respectively), as compared to the flat panel reactor and raceway ponds at 3.0–3.2 and 2.9–3.5 €·kg^{-1}, respectively.

When focusing on Qatar (Al Khor), the lowest biomass production costs of 2.9 €·kg^{-1} is predicted for raceway pond cultivation, followed by 3.1 €·kg^{-1} for a flat panel photobioreactor. These costs are lower than recorded previously by Ruiz et al. (2016) for production in Saudi Arabia (4.0 and 3.2 €·kg^{-1} for raceway ponds and flat panel reactors, respectively), as well as the projections for production in flat panels by Tredici et al. (2016) at 3.2 €·kg^{-1}. The lower costs compared to Ruiz et al. (2016) are most significant for raceway ponds, which can be related back to the higher assumed photosynthetic efficiency (1.92% as compared to 1.2%), based on empirical data from the region.

3.2. Impact of facility scale

Facility scale has a significant impact on the cost of production, with smaller scales having considerably higher costs per unit of biomass

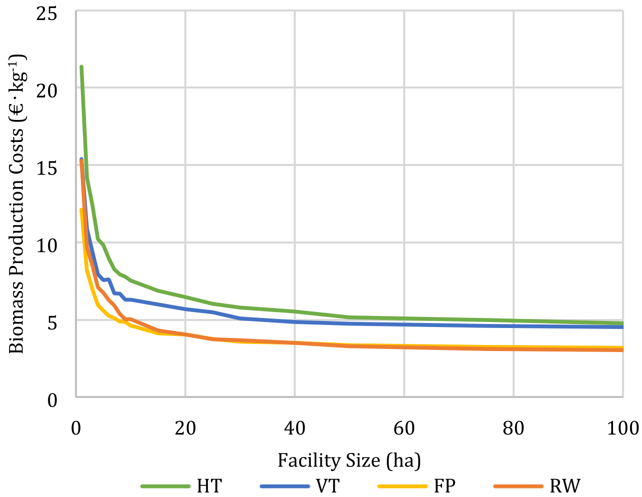

Fig. 2. Projected biomass production costs (€·kg^{-1}) for raceway ponds (RW), horizontal tubular (HT), flat panel (FP) and vertical stacked tubular (VT) photobioreactors, as a function facility size (ha). Location: Qatar (Al Khor).

produced. The above predictions were all based on a 100 ha facility, however reaching such production capacities takes time. Cost predictions showed that the biomass production cost could already be reduced with up to 67% through an increase of scale from 1 to 10 ha (Fig. 2). Scaling up further, to 100 ha, is projected to reduce the production costs with a mere additional 13%. Largest gains are seen in the operation costs (OPEX); at 1 ha, up to 46.7% of the total biomass production costs are for labor (raceway ponds), whilst at 10 ha this is only 15–24% depending on the reactor type. At 100 ha scale, labor costs can even go down to as low as 3.4% for vertical stacked tubular photobioreactors (Fig. 3). Ruiz et al. (2016) indicated already that a scale increase from 1 to 100 ha reduced the production costs, but here we show that the most significant cost benefits – on relative basis – from upscaling are actually realized in the first over-of-magnitude step. This suggests that a modular growth model of multiple smaller production facilities spread out over a wider area as opposed to a low number of major ones might offer a cost-attractive and de-risked project development strategy.

3.3. Temperature

Generally speaking, higher solar irradiances are paired with higher ambient temperatures. Especially in closed cultivation systems, the combination of these two factors can lead to very high culture temperatures if no external cooling is applied (Carvalho et al., 2006). Considering the effects of irradiance, radiation, convection, evaporation and condensation on the heat fluxes of each cultivation system, maximum culture temperatures were estimated for each location by running the model without temperature control (Fig. 4 A). Not surprisingly, due to the lack of evaporative and external cooling, the culture temperature profiles in the closed systems showed higher maxima as compared to the raceway ponds. Furthermore, locational differences in temperature maxima were significant, with differences of Δ 17.7 °C for horizontal tubular photobioreactors, with UAE (Sharjah) having the highest peak temperatures, of up to 68.6 °C for horizontal tubular reactors, and 39.7 °C for raceway ponds.

Monthly average diurnal culture temperatures were also modeled for Qatar (Al Khor) (Fig. 4 B). Maximum daily fluctuation predicted were Δ 30.6 °C, for flat panel photobioreactors without cooling. Such extreme culture temperatures and fluctuations can significantly impact the productivity of a strain, with temperatures above optima rapidly leading to cell death (Ras et al., 2013); a key reason why temperature control through external cooling is necessary. The maximum culture temperature and fluctuations in the open raceway pond were considerably smaller, with a maximum of 39.7 °C, and maximal diurnal fluctuation of

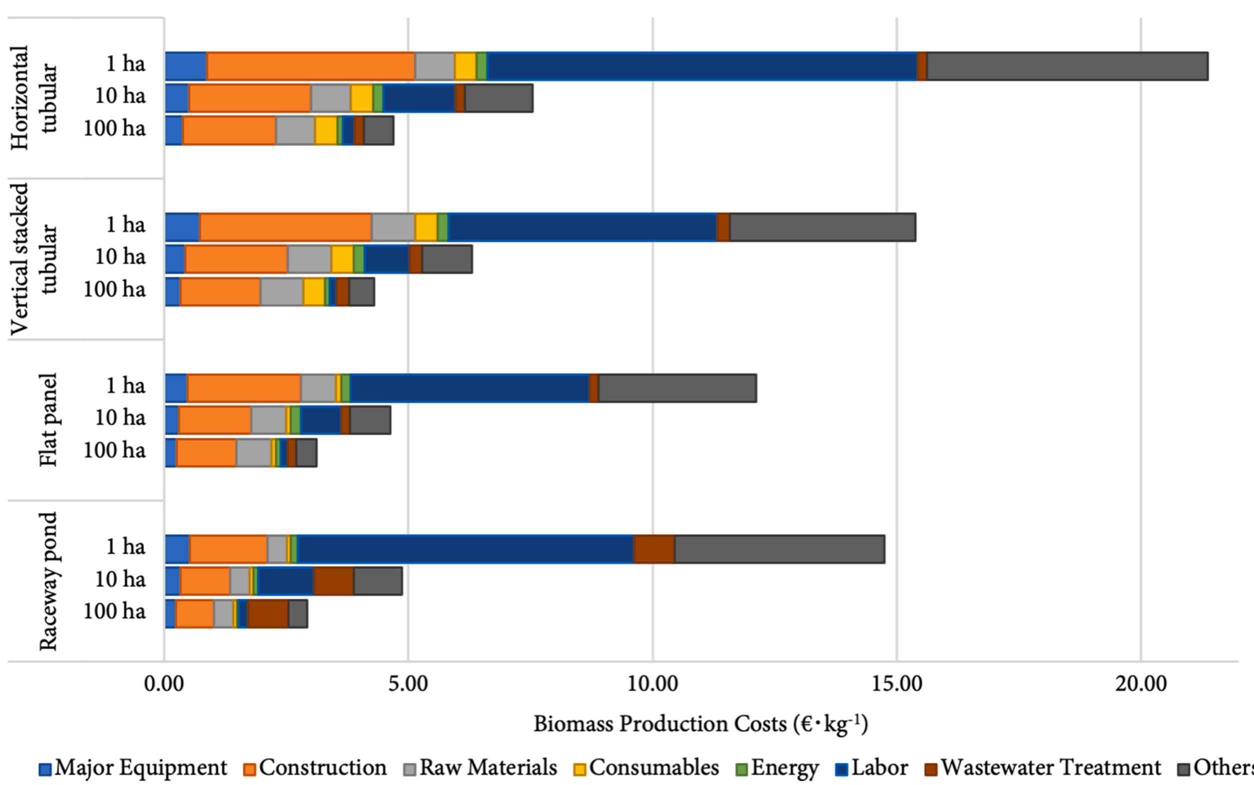

Fig. 3. Cost breakdown of projected biomass production costs in €·kg^{-1}, for a 1, 10 and 100 ha cultivation facility located in Qatar (Al Khor), and different bioreactor types (HT: Horizontal tubular, VT: Vertical stacked tubular, FP: Flat panel, RW: Raceway pond).

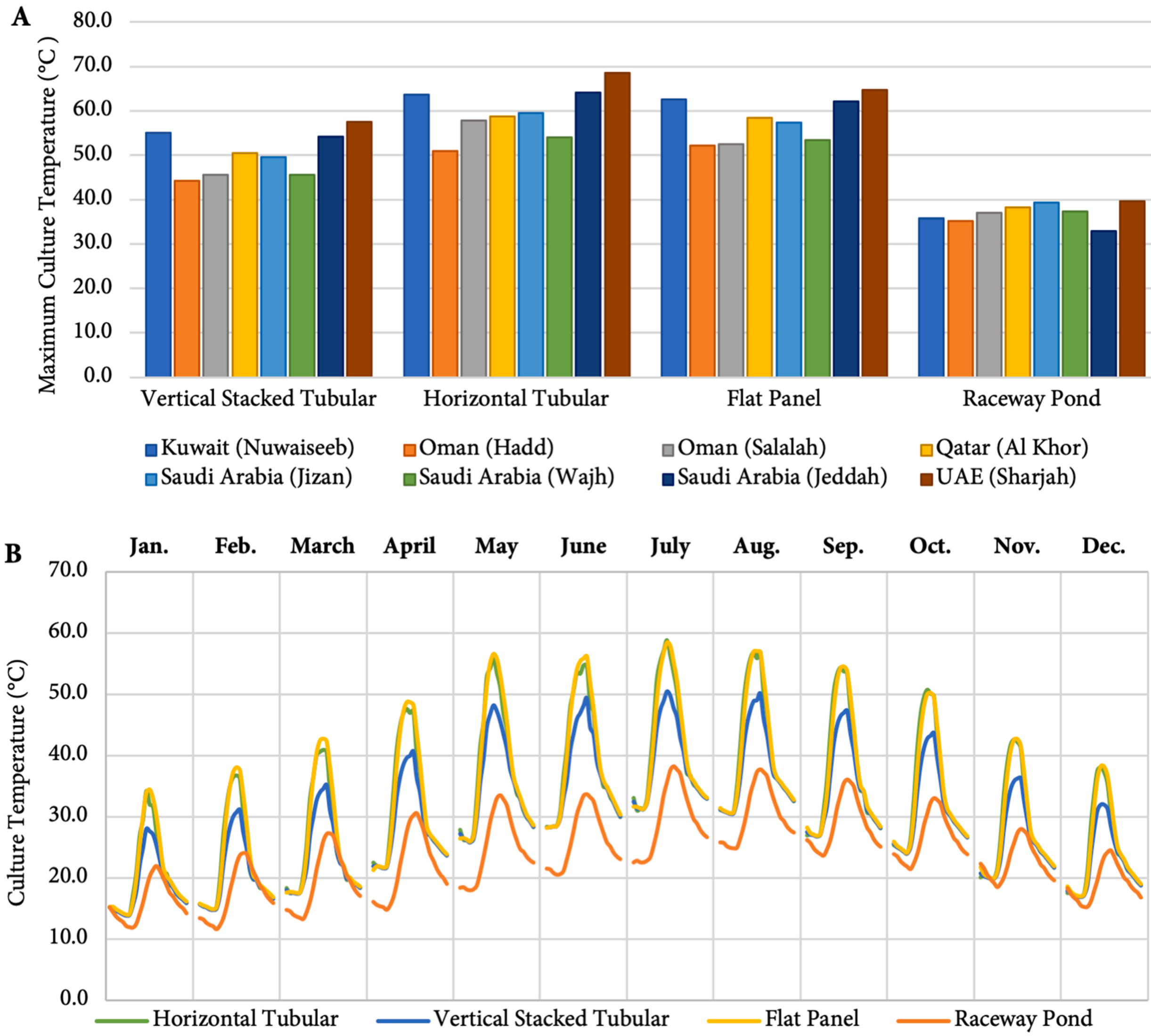

Fig. 4. **A)** Maximum culture temperatures simulated in photobioreactors without cooling for the different GCC locations and **B)** Average diurnal (00:00–24:00 h) temperature profiles simulated for each month, for the different cultivation systems without cooling, for cultivation in Qatar (Al Khor).

Δ 15.9 °C. In this scenario, where the optimum culture temperature is 40 °C, cooling is not required in the raceway ponds. Nonetheless, as the lower temperature is mainly due to evaporative heat losses, this in turn will be paired with concerns of increasing salinities, and requirement for non-saline make-up water. The biological effects of diurnal variations should also be taken into consideration, as this could significantly reduce productivities, and increase operational complexity and risk, depending on the strain applied (Huesemann et al., 2016).

3.4. *Improving the Process: Sensitivity analysis*

In order to optimize the production processes in question, and reduce production costs, further research and development is needed. A sensitivity analysis can help guide research focus to areas of most significant expected impact. In the present study, the impact of photosynthetic efficiency, temperature optima, harvesting methods, operational days, alternative urea and CO_2 sources, and wastewater treatment costs on the biomass production costs of a Qatar-based (Al Khor) production facility were assessed (Fig. 5).

3.5. *Photosynthetic efficiency*

Regardless of reactor type, the foremost parameter driving the biomass production costs was the photosynthetic efficiency. A doubling of PE resulted in a cost reduction of 32.7–42.5% compared to its base case scenario. The second most impactful parameter, specifically for the closed systems, was the culture temperature maximum of the strain. Increasing this parameter to 60 °C, thereby eliminating the need for temperature control (maximum predicted culture temperature in Qatar was 58.8 °C in horizontal tubular reactors) was found to reduce the projected production costs with up to 25%. In raceway ponds there was no benefit of increased temperature optima, as the maximum culture temperature was lower (38.2 °C) compared to the maximum culture temperature set in the base case (40 °C). For flat panel bioreactors, the biomass production costs could be reduced to as low as 1.46 €·kg^{-1} by applying these two improvements – photosynthetic efficiency and temperature optima – alone.

Improvement of photosynthetic efficiencies has been recognized as a major factor towards reducing production costs in several studies (Norsker et al., 2011; Ruiz et al., 2016). In order to approach an optimized design, in particular for the Arabian Peninsula where light is readily available, strains which maintain high photosynthetic

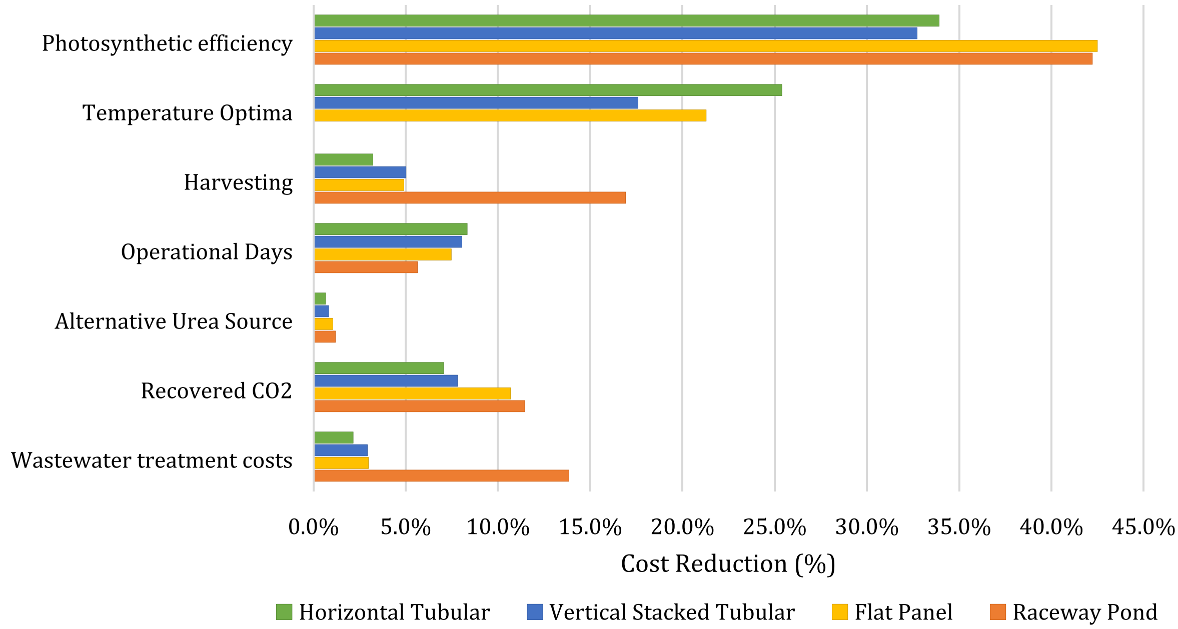

Fig. 5. Sensitivity analysis on biomass production cost for production in Qatar. Reference and improvement scenario parameters can be found in Table 5. Effect of individual parameters on cost is shown in horizontal axis.

efficiencies under high light intensities will be essential (Tredici, 2010). Different approaches have been investigated to optimize photosynthetic efficiencies, both biological (strain selection, strain adaptation) and non-biological (bioreactor design, process optimization) (Nwoba et al., 2019). High light intensities are a common climatic condition across the Arabian Peninsula, and as of such, local strains have the potential of being well adapted to thrive under such conditions. Increasing the bio-prospecting efforts in the region could lead to identification, isolation and application of strains which are optimally adapted to maintain high photosynthetic efficiencies even under high light intensities and temperatures. All in all, establishing long-term outdoor cultivation with high photosynthetic efficiencies will require an interplay between strain selection, bioreactor design, and climate conditions (light and temperature), in order to accomplish the envisioned improvements.

3.6. Wastewater treatment & harvesting

The effect of other improvements on predicted biomass production costs had limited overall impacts on cost reductions, with the exception of harvesting and wastewater treatment for raceway pond cultivation. Due to lower biomass densities, larger culture volumes need to be processed for raceway pond cultivation compared to closed cultivation systems. Reducing the wastewater treatment costs with 50%, either due to implementation of water recycling, or a decrease in volumetric treatment costs, could result in an overall production cost reduction of 13.8%. In closed systems however, reducing the wastewater treatment costs had an impact of only 2.2–3.0% on the overall production costs.

In terms of harvesting, replacing centrifugation with less energy-intensive processes could improve the raceway pond production costs with 16.9%. The impact of harvesting on production cost reductions in closed systems was significantly less, ranging from 3.2 to 5.0%.

3.7. Industrial integration

Integration with industrial 'waste' streams as process input, such as flue gas CO_2 and waste urea, was found to have a slight impact on the production costs as well, with cost reductions of up to 11.5% for flue gas CO_2 utilization and 1.2% for urea sourced from waste urea streams (e.g. bleed from urea production). The use of waste urea for algae biomass cultivation has been demonstrated as a feasible alternative feedstock source by Al-Jabri et al. (2021), and although the cost benefit is limited, other secondary benefits such as reduction of industrial waste can also be taken into consideration.

3.8. Regional product markets

Products derived from algae biomass can be commercialized into roughly four potential markets: energy, chemicals, food & feed, and pharmaceuticals. Downstream processing to selected end-products can add significant value to the biomass, increasing the economic feasibility of the process. Of these markets, it is food & feed which represents the most significant growth- and strategic potential in Arabian Peninsula countries for algae-based products; either to provide feed supplements or substitutes for conventional protein sources. This is primarily caused by the (very) limited local fresh water resources and agricultural land, which sees the Peninsula currently being heavily reliant on imports to sustain both its human- and animal populations (Brown et al. 2018). Replacing such imports with locally produced products could increase the region's food-security and agricultural sustainability.

3.9. Recommendations

In this study, photosynthetic efficiency was found to be the most significant variable influencing the production costs, yet for that reason also introduced the most uncertainty into the model. For raceway pond base-cases, the photosynthetic efficiency used for the predictions was based on empirical data from the region. Such regional data is however not (yet) available for the other cultivation systems. Improvements in photosynthetic efficiency, as well as culture temperature optima of the strain, were found to lead to the most significant reductions in production costs. This is a clear indicator that bioprospecting efforts in the region for photo- and thermo- tolerant strains could be the differentiating factor the algae industry needs for competitive and commercially viable establishment.

A recommended forward route towards validation of these model outcomes would be to conduct regional pilot-scale studies of different reactor types side-by-side, most specifically flat panel photobioreactors and open raceway ponds. Besides productivity data, which can be used to support the assumptions made within the techno-economic analysis, other practical aspects of scale-up can and should be investigated concurrently. For example:

- Impact of ultraviolet radiation levels on long-term integrity of (plastic) bioreactors and associated outdoor facility equipment;
- The effect of sand and dust ingress (which is a prevalent constant in the region's atmosphere) on open cultivation systems and downstream-processing;
- Industrial integration for process inputs, such as carbon dioxide;
- Water management strategies to deal with high levels of evaporative losses during cultivation in open systems.

Studying such aspects at pilot scale will provide the key-insights needed to create a clear road-map towards commercialization of an algae-based industry within the GCC region.

4. Conclusion

The GCC region offers a remarkable potential for algae biomass production, however has seen very few studies into the topic. Production cost projections across multiple cultivation systems and locations indicated that raceway ponds and flat panel photobioreactors are the most credible options for large-scale production, with globally competitive biomass production costs. Strain selection, with a focus on temperature tolerance and photosynthetic efficiency, was identified as the key recommended focus area for future cost reductions. The study outcome confirms the region's credibility as an economically attractive locations for algae production, linking into feed, food and nutraceutical industries.

CRediT authorship contribution statement

Kira Schipper: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Funding acquisition, Writing - original draft. **Hareb Mohammed S.J. Al-Jabri:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition. **Rene H. Wijffels:** Conceptualization, Supervision, Writing - review & editing. **Maria J. Barbosa:** Conceptualization, Supervision, Writing - review & editing, Methodology.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2021.125043.

References

Abu-Rezq, T.S., Al-Hooti, S., Jacob, D.A., 2010. Optimum culture conditions required for the locally isolated *Dunaliella salina*. J. Algal. Biomass. Util. 2, 12–19.

Al-Jabri, H., Das, P., Thaher, M., Khan, S., AbdulQuadir, M., 2021. Potential utilization of waste nitrogen fertilizer from a fertilizer industry using marine microalgae. Science of The Total Environment 755, 142532. https://doi.org/10.1016/j.scitotenv.2020.142532.

Authority for Public Service Regulation (Oman), 2017. Customer Tariffs for Electricity <https://www.apsr.om/en/tariffs> (accessed September 2020).

Banerjee, S., Ramaswamy, S., 2019. Comparison of productivity and economic analysis of microalgae cultivation in open raceways and flat panel photobioreactor. Bioresource Technology Reports 8, 100328. https://doi.org/10.1016/j.biteb.2019.100328.

Borowitzka, M.A., Vonshak, A., 2017. Scaling up microalgal cultures to commercial scale. European Journal of Phycology 52 (4), 407–418. https://doi.org/10.1080/09670262.2017.1365177.

Brown, J.J., Das, P., Al-Saidi, M., 2018. Sustainable Agriculture in the Arabian/Persian Gulf Region Utilizing Marginal Water Resources: Making the Best of a Bad Situation. Sustainability. 10 (5), 1364–1416.

Carvalho, A.P., Meireles, L.A., Malcata, F.X., 2006. Microalgal Reactors: A Review of Enclosed System Designs and Performances. Biotechnol Progress 22 (6), 1490–1506. https://doi.org/10.1002/bp060065r.

Coulson, J.M., Richardson, J.F., Sinnott, R.K., 1991. Chemical engineering Volume 6: Design. Pergamon Press, Oxford.

da Silva, T.L., Reis, A., 2015. In: Algal Biorefinery: An Integrated Approach. Springer International Publishing, Cham, pp. 125–149. https://doi.org/10.1007/978-3-319-22813-6_6.

Das, P., Quadir, M.A., Chaudhary, A.K., Thaher, M.I., Khan, S., Alghazal, G., Al-Jabri, H., 2018. Outdoor continuous cultivation of self-settling marine cyanobacterium Chroococcidiopsis sp. Ind. Biotechnol. 14, 45–53.

Das, P., Thaher, M., AbdulQuadir, M., Khan, S., Chaudhary, A., Al-Jabri, H., 2019a. Long-term semi-continuous cultivation of a halo-tolerant *Tetraselmis* sp. using recycled growth media. Bioresour. Technol. 276, 35–41.

Das, P., Thaher, M., Khan, S., AbdulQuadir, M., Al-Jabri, H., 2019b. The effect of culture salinity on the harvesting of microalgae biomass using pilot-scale tangential-flow-filter membrane. Bioresour. Technol. 293, 122057.

Das, P., Thaher, M.I., Hakim, M.A.Q.M.A., Al-Jabri, H.M.S.J., 2015. Sustainable production of toxin free marine microalgae biomass as fish feed in large scale open system in the Qatari desert. Bioresour. Technol. 192, 97–104.

Das, P., Thaher, M.I., Hakim, M.A.Q.M.A., Al-Jabri, H.M.S.J., Alghasal, G.S.H.S., 2016. A comparative study of the growth of *Tetraselmis* sp. in large scale fixed depth and decreasing depth raceway ponds. Bioresour. Technol. 216, 114–120.

de Vree, J.H., Bosma, R., Janssen, M., Barbosa, M.J., Wijffels, R.H., 2015. Comparison of four outdoor pilot-scale photobioreactors. Biotechnol. Biofuels 8, 1–12.

Endres, C.H., Roth, A., Brück, T.B., 2016. Thermal Reactor Model for Large-Scale Algae Cultivation in Vertical Flat Panel Photobioreactors. Environ. Sci. Technol. 50, 3920–3927.

fxtop, Historical Exchange Rates. < https://fxtop.com/en/historical-exchange-rates.php?MA=0&TR=1> (accessed August 2020).

Harethi, Al, A.H., Hernandez, H.H., 2014. High salinity tolerant microalgae strains, products derived therefrom, and methods of producing the same Pub. No.: US 2014/0113340A1.

Huesemann, M., Crowe, B., Waller, P., Chavis, A., Hobbs, S., Edmundson, S., Wigmosta, M., 2016. A validated model to predict microalgae growth in outdoor pond cultures subjected to fluctuating light intensities and water temperatures. Algal Res. 13, 195–206.

International Trade Administration, Saudi Arabia - Import Tariffs. <https://www.export.gov/apex/article2?id=Saudi-Arabia-import-tariffs> (accessed August 2020).

Kahramaa, Qatar General Electric & Water Corporation, Tariff Calculator <https://www.km.qa/CustomerService/Pages/Tariff.aspx> (accessed September 2020).

Khan, M.I., Shin, J.H., Kim, J.D., 2018. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microb. Cell Fact. 2012 11:1 17, 353.

King Abdullah Petroleum Studies and Research Center, 2018. Electricity Tariffs in Saudi Arabia. <https://datasource.kapsarc.org/explore/dataset/electricity-prices-in-saudi-arabia0/table/?disjunctive.consumption_slab&disjunctive.sector&refine.sector=Agricultural&sort=consumption_slab&refine.year=2018> (accessed September 2020).

Kitto, M.R., Reginald, M., 2011. Effect of summer/winter light intensity and salt on growth kinetics and beta carotene accumulation by *Dunaliella* in open outdoor earthern ponds in a desert island, off UAE coast. J. Algal Biomass Util. 2, 14–21.

Kumar, K., Mishra, S.K., Shrivastav, A., Park, M.S., Yang, J.-W., 2015. Recent trends in the mass cultivation of algae in raceway ponds. Renew. Sust. Energ. Rev. 51, 875–885.

Kuwait News Agency KUNA, 2017. Kuwait's new electricity, water tariffs aims at rationalization - MEW <https://www.kuna.net.kw/ArticleDetails.aspx?id=2605677&language=en> (accessed September 2020).

Mathimani, T., Pugazhendhi, A., 2019. Utilization of algae for biofuel, bio-products and bio-remediation. Biocatal. Agric. Biotechnol. 17, 326–330.

Nandkeolyar, N., Raman, M., Kiran, G.S., Ajai, 2013. Comparative Analysis of Sea Surface Temperature Pattern in the Eastern and Western Gulfs of Arabian Sea and the Red Sea in Recent Past Using Satellite Data. Int. J. Oceanogr. 2013, 1–16.

Norsker, N.-H., Barbosa, M.J., Vermuë, M.H., Wijffels, R.H., 2011. Microalgal production — A close look at the economics. Biotechnol. Adv. 29, 24–27.

Nwoba, E.G., Parlevliet, D.A., Laird, D.W., Alameh, K., Moheimani, N.R., 2019. Light management technologies for increasing algal photobioreactor efficiency. Algal Res. 39, 101433.

Peters, M.S., Timmerhaus, K.D., West, R.E., 2003. Plant Design and Economics for Chemical Engineers, 5 ed. McGraw-Hill Higher Education, Boston.

Ras, M., Steyer, J.-P., Bernard, O., 2013. Temperature effect on microalgae: a crucial factor for outdoor production. Rev. Environ. Sci. Biotechnol. 12, 153–164.

Climate.OneBuilding. Repository of free climate data for building performance simulation <http://climate.onebuilding.org/> (accessed July 2020).

Ruiz, J., Olivieri, G., de Vree, J., Bosma, R., Willems, P., Reith, J.H., Eppink, M.H.M., Kleinegris, D.M.M., Wijffels, R.H., Barbosa, M.J., 2016. Towards industrial products from microalgae. Energy Environ. Sci. 9, 3036–3043.

Salary Explorer, Salary and Cost of Living Comparison <www.salaryexplorer.com> (accessed August 2020).

SAP, General Organization for Social Insurance (GOSI) Contribution Calculation: Basic Monthly Salary <https://help.sap.com/erp_hcm_ias2_2015_01/helpdata/en/81/db4152dd563807e10000000a441470/content.htm?no_cache=true> (accessed August 2020).

Schipper, K., Das, P., Muraikhi, Al, M., Abdul Hakim, M.A.Q.M., Thaher, M.I., Al-Jabri, H.M.S.J., Wijffels, R.H., Barbosa, M.J., 2021. Outdoor scale up of Leptolyngbya sp.: effect of light intensity and inoculum volume on photoinhibition and -oxidation. Biotechnol. Bioeng. doi: 10.1002/bit.27750.

Schipper, K., Fortunati, F., Oostlander, P.C., Muraikhi, Al, M., Al-Jabri, H.M.S.J., Wijffels, R.H., Barbosa, M.J., 2020. Production of phycocyanin by Leptolyngbya sp. in desert environments. Algal Res 47, 101875.

Sea water temperature. Surface temperatures on the coasts. <https://seatemperature.info/> (accessed July 2020).

King Abdullah Petroleum Studies and Research Center. Sharjah Electricity and Water Authority. Electricity Tariff by Authority, Slab Consumption and Sector. 2018. <https://datasource.kapsarc.org/explore/dataset/electricity-tariff-by-authority-slab-consumption-and-sector/table/?disjunctive.authority&disjunctive.sector&disjunctive.consumption_slab&disjunctive.nationality&sort=time_period> (accessed September 2020).

Tredici, M.R., 2010. Photobiology of microalgae mass cultures: Understanding the tools for the next green revolution. Biofuels 1, 143–162.

Tredici, M.R., Rodolfi, L., Biondi, N., Bassi, N., Sampietro, G., 2016. Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP®) plant. Algal Res. 19, 253–263.

Ugwu, C.U., Aoyagi, H., Uchiyama, H., 2008. Photobioreactors for mass cultivation of algae. Bioresour. Technol. 99, 4021–4028.

Vonshak, A., Richmond, A., 1988. Mass production of the blue-green alga *Spirulina*: An overview. Biomass 15, 233–247.

Wang, B., Lan, C.Q., Horsman, M., 2012. Closed photobioreactors for production of microalgal biomasses. Biotechnol. Adv. 30, 904–912.