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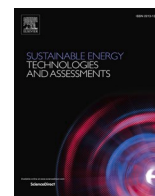
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Thermal regulation of algae cultures in raceway ponds utilizing ground heat: Improving techno-economic feasibility and process sustainability of large-scale algae production in Qatar

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ABSTRACT

There is an increasing drive for developing sustainable alternatives for fuels, foods, feeds, and chemicals. Algae can play a significant role in this, however the commercialization of microalgal biomass is still limited for techno-economic reasons. Open raceway ponds are some of the most competitive systems to produce algae on a large scale, however productivities and techno-economics can be unfavorable when temperature fluctuations cause sub-optimal conditions. Maintaining temperatures nearer to strain-optima through thermal regulation has been shown to increase productivities, however the techno-economic impact of implementation has yet to be addressed. In this study the effect of ground-heat exchanger implementation for thermal regulation of open raceway ponds was evaluated in terms of productivity, production costs and process sustainability. Multiple thermal regulation scenarios were evaluated for two microalgae strains from Qatar, *Pichochlorum maculatum* and *Nannochloris atomus*, and it was projected that thermal regulation could increase annual biomass yields up to 10.0 and 69.6 %, respectively. Biomass production costs were found to be reduced as much as 29.5 %, depending on strain and regulation scenario. Furthermore, a sensitivity analysis identified further means by which energy requirements and production costs could be reduced by 18.9 and 67.2 %, respectively, reaching a biomass production cost of 6.21 €·kg⁻¹.

Introduction

With the increasing global population and subsequent demands for food, feed, fuels, and chemicals, there is an increased need for developing sustainable alternative feedstocks with reduced ecological footprints. Especially in arid regions, such as the Arabian Peninsula, traditional crop agriculture is expensive and unsustainable, often requiring energy intensive controlled (indoor) cultivation, as well as the use of scarce fresh-water resources. For such regions in particular, algae could play an important role as a renewable feedstock, without the need for arable land or fresh water, and capture CO₂ in the process [1]. They hold the potential to support regional developments in sustainable development, through food security, energy transition, decarbonization,

and economic diversification. Globally however, commercial implementation of algae value-chains is still limited, mainly for techno-economic reasons related to achievable productivities and production scale [2,3].

Commercially, algae can be cultivated in different types of cultivation systems, ranging from closed photobioreactors (tubular, flat panel, column etc), or open systems such as raceway ponds. Although raceway systems have lower productivities compared to closed photobioreactors, their techno-economic feasibility is generally regarded as higher – especially for bulk products such as animal feeds or fuels – due to lower capital and operational costs [4–6].

In any system, culture temperature is one of the key parameters influencing productivities: most microalgal species are highly

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productive when culture temperatures range between 20 and 25 °C [7]. However, depending on geographical location, seasonal and daily fluctuations in temperatures can go significantly beyond those limits. Especially in closed photobioreactors temperatures can reach over 60 °C without thermal regulation [6,8]. Even in open raceway ponds in Qatar, where evaporative cooling prevents excessive heating, annual minimum and maximum temperatures can reach 11 and 39 °C, respectively, with daily fluctuations of up to $\Delta 16$ °C [9,10]. In open raceway ponds, indigenous strains that are adapted to grow under local environmental conditions can be key to establishing stable production processes [11], although this can still be accompanied with reduced biomass productivities, when cultivated under sub- or supra-optimal culture temperatures [12].

Regardless of the location or strain, temperature control can support in maintaining culture temperatures within optimal ranges, thereby improving biomass productivities. In closed photobioreactors, implementation of cooling, either using an external cooling water source such as the sea, or a cooling-tower if cooling water is unavailable, is common practice. In raceway ponds however, thermal regulation is not common due to skewed cost to benefit value propositions. Reduced productivities due to non-optimal temperatures are generally accepted, and in extreme cases cultivation is abandoned during unfavorable periods of the year. In some regions, placing cultivation systems in greenhouses to allow for temperature control can be a solution, however overheating and loss of light can negatively affect biomass production [13]. Alternately, varying the depth of raceway ponds can be applied to reduce daily temperature fluctuations, but these alternatives also affect the volumetric productivity or are cost ineffective [14].

One alternative option is the use of a ground-heat exchanger to reduce daily temperature fluctuations, and increase biomass yields. Such a solution can both limit overheating during summer, as well as heat the culture during winter, to maintain temperatures within optimal ranges. A modeling approach was first used to determine the temperature profiles which could be achieved with such a system [9], after which biomass productivities for two indigenous microalgae to Qatar, *Picochlorum maculatum* and *Nannochloris atomus* under the modeled temperature profiles were evaluated empirically [15]. These experiments demonstrated that increased productivities could be achieved with thermal regulation through the theoretical implementation of a ground-heat exchanger, however the economic feasibility and sustainability of such a thermal control system has yet to be demonstrated.

The objective of the current study was to define in detail, the techno-economic feasibility and energy efficiency of using ground heat exchangers to improve algal biomass production in open raceway ponds in Qatar. Various process and location dependent inputs such as, empirical photosynthetic efficiencies (PE), historical climate data, equipment, electricity and labor costs, were set into a techno-economic model to obtain different productivity projections, with a detailed cost breakdown. Furthermore, a sensitivity analysis determining the individual as well as combined impacts of different parameters such as cultivation scale, pond size and harvesting technologies, on total costs and energy efficiency was performed to identify the most sustainable and cost-effective operational process. The results from this study will give a clear path for a sustainable production of microalgae biomass in Qatar.

Materials and methods

The techno-economic analysis was performed based on previously developed models by Ruiz et al (2016) and Schipper et al (2021), with additional modifications to assess the techno-economic impact of thermal regulation using ground heat exchangers [6,10]. The model relies on strain and location dependent inputs, such as biomass productivities and climate data, as well as costs of equipment, labor, electricity, and consumables. Modifications are described here, as well as the source of the model variables.

Model boundaries & basic assumptions

The model assumes a 1-hectare algae production facility located in Al Khor, Qatar, starting from seawater intake & sterilization, cultivation, and downstream processing to a dry biomass powder as final product. In Fig. 1 the process flow diagram is illustrated, detailing all included major equipment as well as other process costs incorporated.

Under the base-case scenario the model assumes that algae biomass is produced in open raceway ponds, each consisting of ring-channel system forming a single loop, having a surface area of 1000 m², culture depth of 0.2 m, and lined with reinforced thermo-sealed PVC. The culture is circulated at a liquid velocity of 0.25 m·s⁻¹ using a paddle-wheel. The model was modified to incorporate paddle wheel costs on an individual pond basis (€·pond⁻¹), rather than a total surface area basis (€·ha⁻¹). Following the cultivation, the culture is harvested, and two dewatering steps, microfiltration and centrifugation are applied, prior to spray-drying to obtain the biomass powder as the final product. Constant harvesting and filtration are assumed (24 h·d⁻¹), at a concentration factor 10, and the filtrate from the microfiltration step is recycled to the culture. Concentrated biomass is stored in the harvest storage tank until centrifugation, for which daily operation hours are assumed to be 12 h·d⁻¹. Following, the solid fraction of the centrifugation, a 10 % DW slurry, is dried in a spray drier, whilst the liquid is treated as wastewater with associated costs [6].

The cost of major equipment and materials was obtained from suppliers where possible, or derived from literature. Where needed, prices were corrected for inflation using the Harmonized Indices of Consumer Prices (HICP) for the European Union. A further detailed overview of the capacity, power requirements and costs for each of the mentioned equipment and materials for the cultivation and harvesting processes can be found in Appendix A.

Heat-fluxes and temperature control

As per Ruiz et al (2016) [6], culture temperatures were estimated based on available empirical climate data [16], taking into consideration heat fluxes (Q) in watts (W) of irradiation, radiation, evaporation and convection [14,17,18]. Pruvost et al (2019) found that ground temperatures (constant at 28 °C in Qatar) also significantly impacted the temperature profiles of open race-way pond cultures, with a positive effect especially in winter (heating) [9]. For this reason, additional ground conduction heat-fluxes were also incorporated into the model (Eq. (1)) to calculate the total culture heat flows (ϕ') in watt (W), Eq. (2)).

$$Q_{\text{ground conduction}} = A_C \cdot \frac{h_G}{0.1} \cdot (T_{\text{ground}} - T_C) \quad (1)$$

$$\phi' = Q_{\text{irradiance}} - Q_{\text{radiation}} - Q_{\text{evaporation}} - Q_{\text{convection}} + Q_{\text{ground conduction}} \quad (2)$$

in which A_C is the culture surface area in m², h_G is the heat transfer coefficient of the ground (sand), and T_{ground} and T_C are the ground and culture temperature (°C), respectively. Culture temperatures were calculated on an hourly basis, and in the scenario where $T_{C,\text{min}} < T_C < T_{C,\text{max}}$, no temperature control was applied. However, if T_C exceeded the maximum culture temperature ($T_{C,\text{max}}$ °C), or dropped below the minimum temperature setpoint ($T_{C,\text{min}}$ °C), required cooling (Q_{cooling} , W) or heating (Q_{heating} , W) fluxes to maintain T_C within the temperature boundaries were determined (see Appendix B).

The required thermal regulation is achieved by one pump and two equally sized heat exchangers per pond: one culture submerged heat exchanger to control the culture-temperature, and one sub-surface ground heat exchanger to regenerate the cooling water (Fig. 2).

The required heat exchanger sizing (A_{HE} , m²) was determined based on thermal regulation requirements, calculated as per Eq. (3):

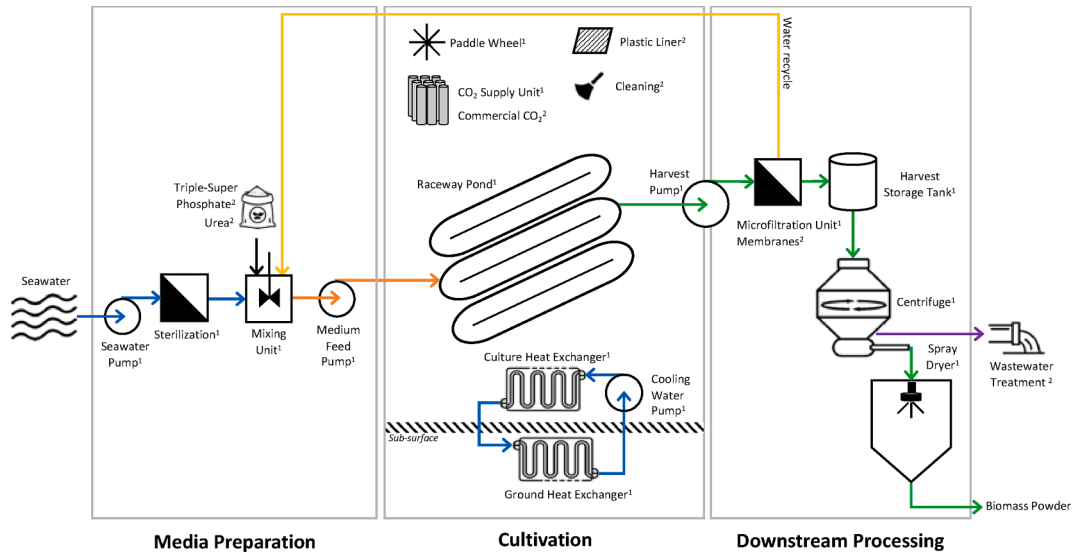


Fig. 1. Process Flow Diagram of model-incorporated components, with ¹ indicating major equipment and ² indicating consumable costs considered. Other operational costs, such as electricity and labor, are considered separately (see text).

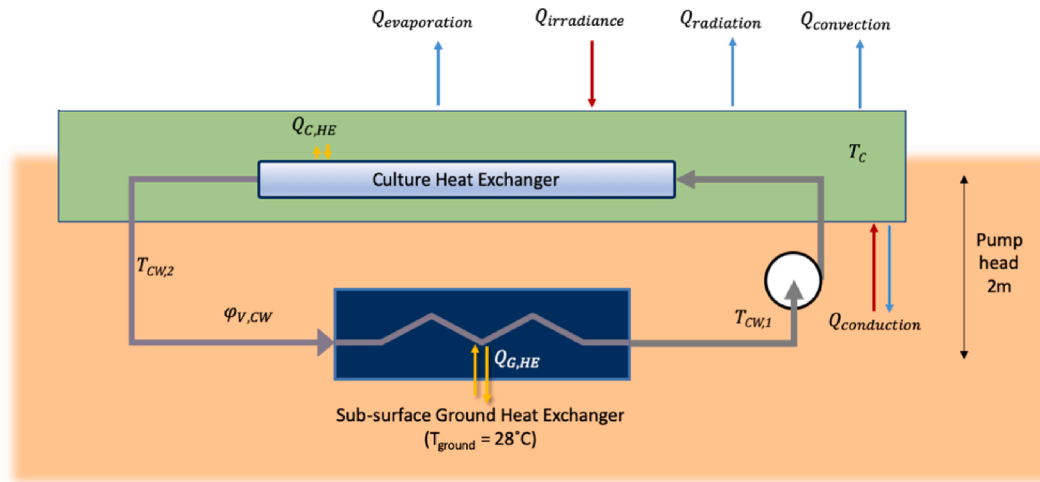


Fig. 2. Assumed heat flows and heat exchanger configuration adopted in the simulation, including a culture heat exchanger submerged in the raceway pond (green), and a sub-surface ground heat exchanger (blue). Adapted from Pruvost et al (2019) [9]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$A_{HE} = \frac{Q_{cooling/heating}}{h \cdot \Delta T_{CW,HE}} \quad (3)$$

in which h is the heat transfer coefficient, which is estimated at $825 \text{ W}\cdot\text{m}^{-2}\cdot\text{C}^{-1}$, and $\Delta T_{CW,HE}$ is the difference between the cooling water temperature entering and leaving the culture heat exchanger ($^{\circ}\text{C}$). The latter was determined assuming a constant ground temperature of 28°C [9], and a heat exchanger efficiency of 75 %. For the pumping requirements, the volumetric flow of cooling water ($\varphi_{V,CW}$, $\text{m}^3\cdot\text{h}^{-1}$) required to achieve the temperature control heat fluxes ($Q_{cooling/heating}$), was determined by Eq. (4):

$$\varphi_{V,CW} = \frac{Q_{cooling/heating}}{C_p \cdot \rho \cdot \Delta T_{CW,HE}} \quad (4)$$

In which C_p and ρ are the assumed specific heat capacity ($4186 \text{ J}\cdot\text{kg}^{-1}\cdot\text{C}^{-1}$) and density ($1027 \text{ kg}\cdot\text{m}^{-3}$) of the culture liquid. Both heat exchanger sizing and pump flow requirements were calculated per hour, and maximum values (i.e. winter or summer extremes) were used to determine equipment costs (CAPEX). Heat exchanger associated

operational costs (OPEX) were defined as the energy consumption needed for the pump. A breakdown of the heat exchanger sizing for the different scenarios, and associated costs can be found in Appendix B.

Empirical data model inputs

In the current study, two microalgae strains native to Qatar were assessed for their techno-economic potential: *Picochlorum maculatum* (MG149785) and *Nannochloris atomus* (KM985399), hereafter referred to as *P. maculatum* and *N. atomus*, respectively. Previously obtained empirical data for biomass productivities and PEs of *P. maculatum* and *N. atomus*, under various seasonal light and temperature profiles (winter, summer and extreme summer), with and without temperature regulation, were used as inputs for the current model [15]. Annual average PEs were determined as the average of seasonally determined PEs for Qatar's three major seasons; Summer (March, August, September, October) Extreme Summer (April, May, June, July) and Winter (November, December, January, February). Other empirical data from Rasheed et al (2022) applied to the model was operational days

(*P. maculatum* could be cultivated year-round, whilst *N. atomus* could not be cultivated in extreme summer), as well as the regulated temperature profiles for temperature-controlled conditions (Table 1). For year-round cultivation, 300 operational days were assumed, considering down-time requirements for maintenance, new cultures, possible contingencies or bad weather [6].

Scenarios & optimization

The techno-economics were evaluated for various production scenarios: initial evaluations for thermal regulation assumed cultivation of *P. maculatum* and *N. atomus*, without thermal regulation, with full thermal regulation (summer cooling and winter heating), and with partial regulation (winter heating only). Further optimization studies were then conducted on the best thermal scenario (base-case) to improve the techno-economics through alternative drying techniques (spray-drying vs. drum-drying), increasing pond size (1000 m² vs. 2500 m²), and finally the impact of cultivation area (1 ha vs. 10 ha) was also evaluated.

Results & discussion

Thermal regulation using ground heat exchangers: Potential to improve microalgal biomass productivities

Based on climate data inputs, the culture temperature profiles for a raceway pond located in Qatar were simulated, and can be found in Fig. 3 A. Under non-regulated conditions, the culture temperatures ranged from 15.2 and 37.3 °C in winter and summer, respectively. Rasheed et al (2022), however, found that maintaining the culture temperature between 23.2 and 31.6 °C, can increase the annual PEs by 7.9 and 37.9 % for *P. maculatum* and *N. atomus*, respectively, compared to non-regulated conditions [15]. This can be achieved through thermal regulation: a ground heat exchanger was modeled to be able to obtain the optimal culture temperature ranges, and the required heat exchanger capacity was determined (Fig. 3 B).

Although the same heat exchanger can be applied for both summer cooling and winter heating, Fig. 3 B shows that the heat exchanger capacities needed vary between the two seasons. To achieve winter heating to maintain a minimum culture temperature of 23.2 °C, 431 W·m⁻² heat exchanger capacity is required. For summer cooling however, a larger heat exchanger capacity of 659 W·m⁻² is needed to maintain culture temperatures below 31.6 °C. This translates to required heat exchanger areas of 17.3 and 35.2 % of the culture surface area, for winter cooling and summer heating, respectively.

The goal of the implementation of the heat exchanger is to improve biomass productivities, and reduce biomass production costs, thereby increasing the techno-economic feasibility of the production process. This is dependent on extent to which the heat exchanger can improve the productivities, balanced with the additionally required capital and operational costs for implementation. Whilst for *N. atomus* summer

cooling is essential to maintain year-round productivities and increase PEs, for *P. maculatum* the increase in PE for (extreme) summer cooling is insignificant (Table 1). For this reason, besides scenarios with and without thermal regulation, an additional scenario with only winter regulation was included. Annual biomass productivities (ton·ha⁻¹·year⁻¹) were estimated using empirically found seasonal PEs combined with climate data (10-year average global solar irradiance), and associated production costs (€·kg⁻¹) were estimated for *P. maculatum* and *N. atomus* under the three thermal regulation scenarios, which are shown in Fig. 4 A and B, respectively.

Without temperature regulation, annual averaged areal biomass productivities for *P. maculatum* and *N. atomus* were estimated based on empirical data, at 20.24 and 10.25 g·m⁻²·d⁻¹, respectively, corresponding to total annual productivities of 60.72 and 25.02 ton·ha⁻¹·year⁻¹ (Fig. 4 A). The large difference is contributed to the strain-dependent PEs, as well as assumed cultivation days for each strain: under extreme summer conditions *N. atomus* cannot be cultivated under non-regulated conditions, where *P. maculatum* can be cultivated year-round. Implementation of thermal regulation in both winter and summer was estimated to increase annual biomass productivity potentials by 69.6 and 7.9 %, to 42.4 and 65.5 ton·ha⁻¹·year⁻¹ for *N. atomus* and *P. maculatum*, respectively. Only winter regulation increases biomass productivity potentials with 5.2 and 10.0 % for *N. atomus* and *P. maculatum*, respectively. When comparing to other similar techno-economic studies for microalgae production, annual biomass productivities range from 20 to 72 ton·ha⁻¹·year⁻¹ for raceway pond cultivation of various algae species across a range of geographical locations [14,19,20]. Although, according to Tredici (2007), productivities rarely exceed 47 ton·ha⁻¹·year⁻¹ [21]. The improvements in biomass productivity through heat exchanger implementation clearly indicate the benefit of implementing thermal regulation on biomass productivities, however also shows that its effect is highly strain dependent.

Without thermal regulation, total annual costs for the production facility, consisting of capital (assuming a 15 year depreciation), consumable (such as liners and membranes), raw material (nutrients, carbon dioxide, etc), energy, labor and maintenance costs, were found to be 1.13 M €·year⁻¹ irrespective of strain. On a biomass production cost basis, values of 18.80 and 44.78 €·kg⁻¹ were found for *P. maculatum* and *N. atomus*, respectively (Fig. 4 B). Heat exchanger implementation for full and winter thermal regulation scenarios, requiring a surface area of 35.2 and 17.3 % of total culture area, respectively, increased the total annual costs by 19.0 and 10.6 %, respectively. However, with full thermal regulation, biomass production costs for *N. atomus* decreased by 29.5 %, to 31.56 €·kg⁻¹, as productivities showed a significant increase as compared to no thermal regulation scenarios. Of the biomass production costs, 15.4 % was related to heat exchanger implementation (CAPEX 3.95 €·kg⁻¹) and operation (OPEX 0.92 €·kg⁻¹).

For *P. maculatum*, increased productivities due to the implemented thermal regulation were accompanied by increased biomass production costs (9.7 %) for full thermal regulation, however for winter regulation,

Table 1

Strain, seasonal, and regulation dependent cultivation parameters used as inputs for the described TEA model. The different thermal regulations implemented are presented in the table as 'none' (no thermal regulation), 'full' (thermal regulation for both summer cooling and winter heating), and winter (thermal regulation for winter heating only).

Strain	<i>P. maculatum</i>			<i>N. atomus</i>		
	None	Full	Winter	None	Full	Winter
Thermal Regulation						
PE (%)	Summer ^a	3.63	3.44	3.63	1.89	1.89
	Extreme Summer ^a	1.34	1.38	1.34	–	0.68
	Winter ^a	1.91	2.59	2.59	1.6	1.76
	Annual Average	2.29	2.47	2.52	1.16	1.60
Cultivation days	300	300	300	244	300	244
Maximum Culture Temp. (°C)	37.3	31.6	38.2	37.3	31.6	38.2
Minimum Culture Temp. (°C)	15.2	23.2	23.2	15.2	23.2	23.2

^a Rasheed et al (2022)[15].

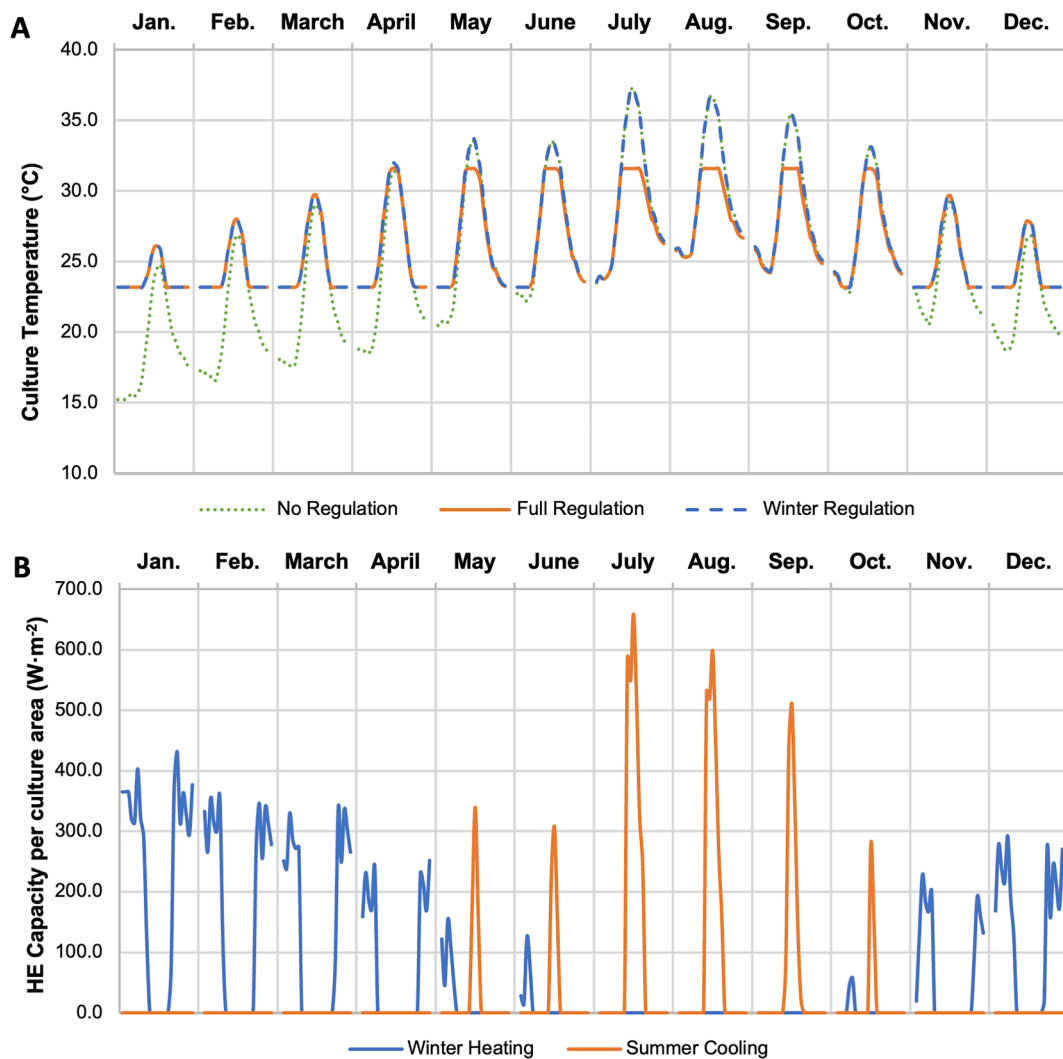


Fig. 3. A) Culture temperature profiles obtained for the different scenarios: no thermal regulation (green), full thermal regulation during summer and winter (orange) and winter regulation only (blue). B) Heat Exchanger (HE) capacity requirements ($\text{W}\cdot\text{m}^{-2}$) calculated, necessary to maintain culture temperatures below $31.6\text{ }^{\circ}\text{C}$ (summer cooling, blue) and above $23.2\text{ }^{\circ}\text{C}$ (winter heating, orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

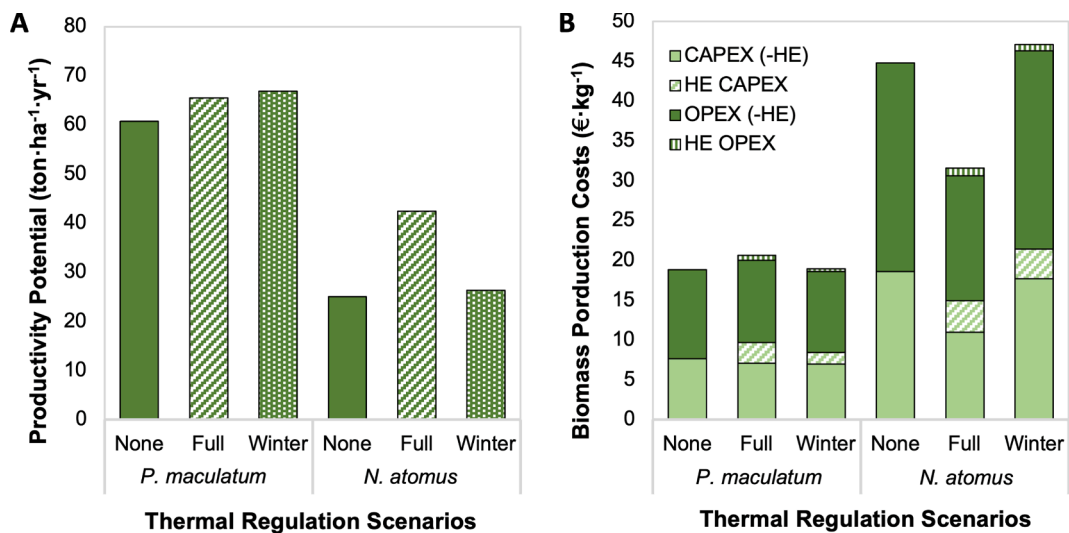


Fig. 4. A) Modeled biomass productivities ($\text{ton}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$), and B) Total biomass production costs ($\text{€}\cdot\text{kg}^{-1}$, CAPEX and OPEX), for *P. maculatum* and *N. atomus*, without thermal regulation (none), full thermal regulation (full), and only winter regulation (winter).

production costs remained similar compared to non-regulated scenarios. This is mainly contributed to the ability of the strain to be cultivated under summer and extreme summer conditions without the need for cooling, contrary to *N. atomus*. Nevertheless, as winter heating still contributed to an increased biomass productivity, whilst costs were not significantly increased, this presents a feasible option to improve productivities and thus profits, without increasing facility size.

Although thermal regulation for closed photobioreactor cultivation of microalgae is an industry standard, raceway pond cultivation is usually considered without. Only a limited number of studies have shown the effect of thermal regulation on biomass productivities in open raceway ponds, with increases ranging from 44 to 60 % [22,23]. Besides the conventional heat exchanger design, an alternative method for temperature regulation was also suggested by Crowe et al (2012) and Waller et al (2012); the algae raceway integrated design (ARID) pond, which consist of a series of basins with varying depths, and a 1.5 m deep canal [24,25]. The system regulates temperature by adjusting the water surface area and thus regulating energy transfer between the culture liquid and the atmosphere, however economic feasibility studies on this system are not yet published. Ryu et al (2019) is one of the only studies found that evaluates the techno-economics on heat exchanger integration for raceway pond production, using a co-localized power-plant as the source of heat for a culture-submerged heat exchanger [22]. Similarly to the current study, Ryu et al found that even though the overall costs increased, increased productivities still led to a 28 % reduction in biomass production costs, from 7.12 to 5.13 US\$·kg⁻¹.

Although full thermal regulation of culture temperatures can lead to significant cost-reductions, strains' tolerance to temperature extremes can increase techno-economic feasibility of algae production in hot arid climates such as Qatar. Such was also suggested by Barten et al (2021), who showed that microalgae species capable of growing at 40 °C, can reduce production costs by 26.2 %, with a possibility for further cost reductions for growth at 45 °C [26]. As per Rasheed et al (2022), *P. maculatum* showed a higher tolerance towards summer and extreme summer cultivation, which reduced the need for summer cooling, although winter heating did show productivity benefits [15]. Following this, by implementing heat exchangers with smaller surface area as required for only winter regulation (17.3 %), and applying such for limited summer cooling, the strains will be subjected to limited periods of less-ideal temperatures during summer, which can have moderate positive effects on productivity, providing a better balance between increased costs and productivities.

Overall, the higher productivity and lower biomass production costs with thermal regulation only during winter seasons, led to the selection of *P. maculatum* over *N. atomus* as a potential strain for further

development for cultivation in Qatar. Nevertheless, the biomass production costs for *P. maculatum* under this 'base-case scenario' were still relatively high, at 18.91 €·kg⁻¹, which is why subsequent investigations focused on the improvement of the production process, to further reduce production costs, increase techno-economic feasibility as well as process sustainability.

Improvement scenarios for increasing techno-economic potential of PM

In the base-case scenario, a cultivation area of 1 ha was assumed, with 10 ponds of 1000 m² each, and biomass harvesting was achieved through centrifugation coupled with spray-drying. Looking into the cost breakdown of the biomass production costs for this scenario, construction, labor, and major equipment are the largest contributors to the costs, at 33.4, 26.3 and 11.2 %, respectively (Fig. 5 B). In order to find means to reduce the biomass production costs, a sensitivity analysis was performed, analyzing the effect of varying process inputs concerning pond size, facility size and harvesting, to identify the best process scenario with the lowest biomass production costs. In Fig. 5 A, the individual, as well as combined effects of the proposed process improvements on biomass production costs are shown, coupled with a cost-breakdown for each of the scenarios (Fig. 5 B).

The first potential improvement to the base-case evaluated the impact of increasing the pond size from 1000 m² to 2500 m², whilst maintaining the same total culture area, thus reducing pond number from 10 to 4 per hectare. Increasing the pond size allowed for the implementation of less, although larger, heat exchangers to achieve the required thermal regulation, reducing the required number of pumps as well. Modeled projections showed a minor reduction in major equipment and construction costs (both -6.9 %), as well as energy costs (-5.9 %), with other costs unaffected, leading to an overall minor reduction of 3.8 % on biomass production costs. In spite of the slightly reduced biomass production costs, considerations for increasing the pond size should be balanced with the increased risks of culture loss (e.g. with contamination), which could reduce annual productivities, as well as with the possible negative effect of larger pond-sizes on biomass productivities due to decreased mixing frequencies which are not accounted for within the current model [27].

In the subsequent investigated improvement scenario, spray-drying was replaced with drum-drying. Drum-driers are generally less expensive as compared to spray-driers and present low operation costs, however there is a possibility of slight degradation in nutritional quality of the biomass – although some studies have now suggested improvements that can overcome this disadvantage [28]. The techno-economic

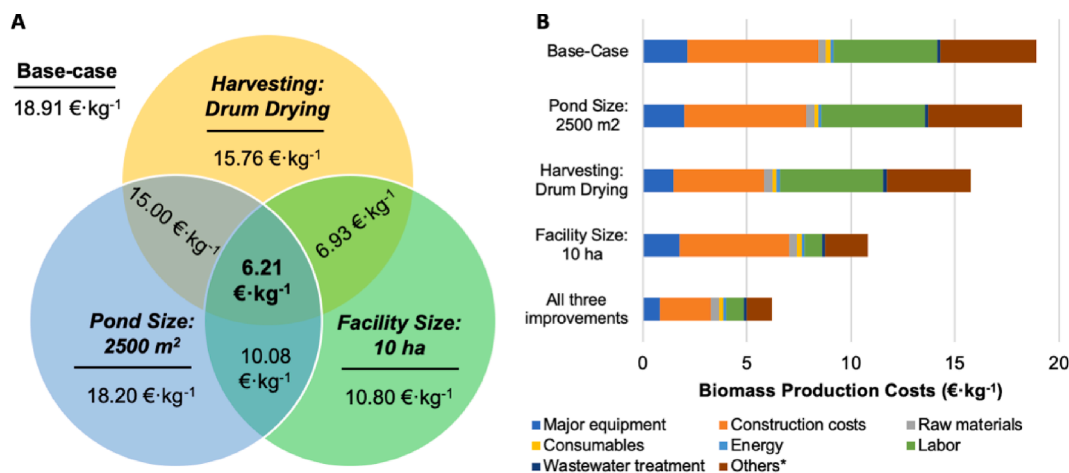


Fig. 5. Impact of (combined) improvement scenarios of harvesting (spray drying vs. drum drying), increasing pond size, and increasing facility size for *P. maculatum* on A) overall biomass production costs and B) production cost breakdowns (*Others indicating Plant Overhead, Maintenance, Operating Supplies and Contingencies).

effect of replacing spray-drying with drum-drying was mainly seen in the major equipment and construction costs, both of which reduced with 30.6 % compared to the base-case scenario. A further minor reduction was seen for energy requirements (-6.1 %), together reducing the estimated biomass production costs with 16.6 % as also observed by Fasaei et al (2018) while replacing spray-drying with drum-drying [29].

Finally, increasing the facility size ten-fold, to 10 ha, showed the potential for a drastic biomass production cost reduction of 42.9 %, to 10.80 €·kg⁻¹. The most significant reductions were found for labor costs (83.3 %), related to the non-linear relation between facility size and required labor force [30]. Similar trends in reduced production costs with increased facility size, often mainly contributed by reductions in labor costs, were also found by Tredici et al (2016), Vázquez-Romero et al (2022), and Fasaei et al (2018) [29,31,32]. Looking into the combined effects of the three different improvement scenarios studied, the lowest projected biomass production costs for *P. maculatum* with thermal regulation in winter was 6.21 €·kg⁻¹, a 67.2 % reduction compared to the base-case scenario. Comparing the found biomass production costs to existing TEA studies for open raceway pond production, there is a wide range of reported values, from 4.95 €·kg⁻¹ [20] and 2.9 €·kg⁻¹ [10], to as low as 0.83 €·kg⁻¹ [33] and 0.67 €·kg⁻¹ [19]. Large variations are attributed not only to different strains and geographical locations, but largely to TEA boundaries and basic assumptions which vary significantly across the studies. For example, some studies assume operation 365 d·year⁻¹ [19] whilst the current study assumes 300 d·year⁻¹, which is conservative compared to the standard 330 days by NREL [34]. Furthermore, assumptions in production scale, which ranged from 1 and 10 ha for this study, up to over 2000 ha (5000 acres) for other studies [34], as well as depreciation costs, harvesting steps, and other aspects associated with capital and operational costs, vary significantly across the different studies. Applying such further improved, but yet to be accomplished scenarios (330 d·year⁻¹ at 2000 ha scale, and 4 ha ponds as per [34]) with the best-case scenario with *P. maculatum*, could further reduce the production costs with 36 % (data not shown), although these costs are expected to be an overestimation, which could be further decreased through reevaluating equipment scales and associated capital costs within the model.

Scenario effects on process sustainability

Although crucial, production costs are not the only factor contributing to the overall commercial feasibility of the production process. To

Table 2

Combination of assessed scenarios for thermal regulation, and process improvements for *N. atomus* and *P. maculatum*. *N. atomus* was not considered for non-thermal improvement scenarios due to its lower techno-economic feasibility compared to *P. maculatum*.

#	Strain	Thermal Regulation	Harvesting Method	Facility Size	Pond Size
	[-]	[-]	[-]	ha	m ²
-1	<i>N. atomus</i>	None	Spray Drying	1	1000
-2		Full	Spray Drying	1	1000
-3		Winter	Spray Drying	1	1000
-4	<i>P. maculatum</i>	None	Spray Drying	1	1000
-5		Full	Spray Drying	1	1000
BC		Winter	Spray Drying	1	1000
1		Winter	Drum Drying	1	1000
2		Winter	Spray Drying	1	2500
3		Winter	Drum Drying	1	2500
4		Winter	Spray Drying	10	1000
5		Winter	Spray Drying	10	2500
6		Winter	Drum Drying	10	1000
7		Winter	Drum Drying	10	2500

an increasing degree, sustainability, and more specifically energy efficiency, is also a vital aspect which needs further consideration. Therefore, besides a production cost evaluation, energy demand was also assessed (Fig. 6 A) for each of the different scenarios (Table 2).

Fig. 6 A shows that all scenarios with *N. atomus* (-1, -2 and -3) have the highest costs as well as energy requirements, per kg of biomass produced. *N. atomus* had considerably lower biomass productivities as compared to *P. maculatum*, and even though full thermal regulation (-2) and associated productivity increases, reduced the production costs and energy requirements, both are still considerably higher as compared to all scenarios with *P. maculatum*. Looking into the different thermal regulation scenarios for *P. maculatum*, no thermal regulation (-4), and only winter regulation (BC) have very similar costs (18.80 and 18.91 €·kg⁻¹) and energy requirements (10.28 and 10.58 kWh·kg⁻¹, respectively). Thus, the increase in biomass productivities resulting from winter thermal regulation, nearly fully compensate for the increased energy requirements of thermal regulation.

Full thermal regulation for *P. maculatum* was already shown to be less favorable from a production cost perspective (Fig. 4 B), and this was further reinforced from an energy perspective, having a 20.1 % higher energy demand as compared to only winter regulation, without additional benefits of increased productivity. When looking into the further

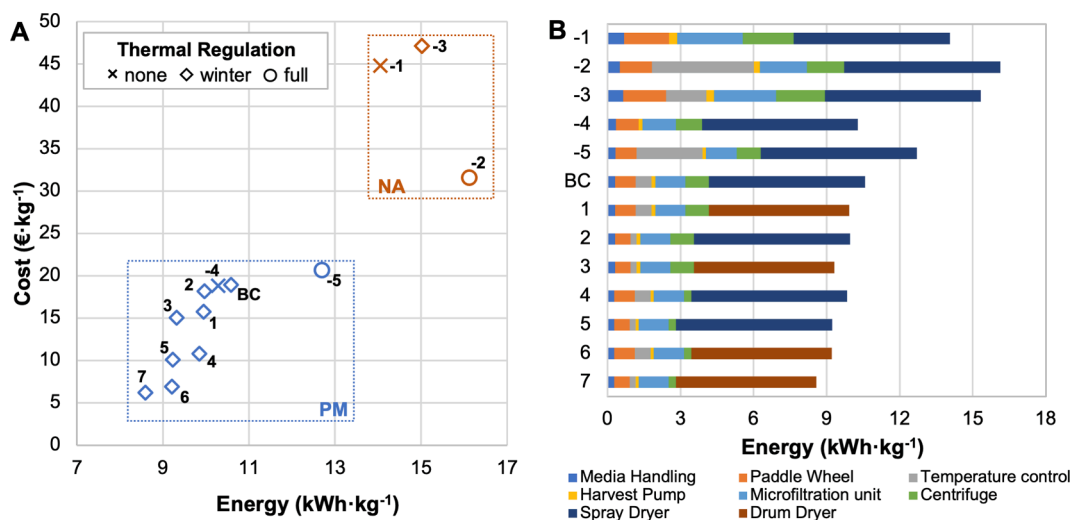


Fig. 6. A) Biomass production costs (€·kg⁻¹) vs. biomass production energy requirements (kWh·kg⁻¹), and B) biomass production energy requirements breakdown (kWh·kg⁻¹), for *N. atomus*, and *P. maculatum*, under no, full and winter thermal regulation, as well as improvement scenarios for *P. maculatum*. BC refers to base-case scenario for *P. maculatum*. Numbering of different scenarios is given in Table 2.

improvement scenarios for *P. maculatum*, increasing pond and facility size, as well as replacing spray-drying with drum-drying, considerable shifts can be found for energy requirements, increasing the process's sustainability. For example, increasing the pond-size reduces the number of pumps needed for circulating heating liquid through the heat exchangers, reducing the energy requirements associated with thermal regulation by 62.8 %, from 0.65 to 0.24 kWh·kg⁻¹. Although the energy requirement reduction when replacing spray drying with drum drying is only 10 %, as it is the most energy-intensive step in the whole production process (58–69 % of total energy requirements), it does have a significant impact on the overall energy demand. When increasing facility scale, minor energy requirement improvements come from culture handling (media preparation, harvesting etc.), but the majority is contributed to centrifugation (68.9 % reduction), as a larger centrifuge has a lower energy requirement per volume of culture processed. The three individual improvement scenarios for alternative harvesting, pond size and facility size, reduced the total biomass-production energy requirements with 6.1, 5.9 and 6.9 %, respectively, with all three combined reducing the requirements by 18.9 %, to 8.6 kWh·kg⁻¹.

Future recommendations

The results show that thermal regulation using ground heat exchangers is a promising way to increase biomass productivities in raceway ponds in Qatar, however careful consideration must be made to ensure increased costs are matched with increased productivities. One of the key recommendations for further improvement would be a more in-depth study of strain temperature optima, such as lower and upper operating ranges, and tolerance of short-duration exposure to sub- and supra-optimal temperatures. This information could then be applied to further maximize productivities, with minimal thermal regulation requirements. This could improve the outcomes by allowing for partial thermal regulation, based on maximum capacities of implemented heat exchangers (e.g. limited summer cooling with heat exchangers sized for full winter thermal regulation).

Conclusion

Thermal regulation of raceway ponds through ground heat exchangers is a simple yet effective solution for improving microalgal mass-scale production in arid regions such as Qatar. The benefit of thermal regulation was found to be highly strain dependent, where thermotolerant strains require lower capacity heat exchangers to improve productivities (only winter heating), and other strains require thermal regulation across multiple seasons. Under specific scenarios, the additional costs and energy requirements of ground heat exchanger implementation was compensated for by increases in biomass productivity, leading to a promising application, balancing thermal regulation implementation costs, techno-economic feasibility and sustainability.

CRedit authorship contribution statement

Rihab Rasheed: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Kira Schipper:** Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Imma Gifuni:** Methodology, Supervision, Writing – review & editing. **Hareb Al Jabri:** Supervision, Writing – review & editing, Methodology, Supervision, Validation, Writing – review & editing. **Maria J. Barbosa:** . **Olivier Gonçalves:** Supervision, Writing – review & editing. **Jeremy Pruvost:** Conceptualization, Supervision, Validation, Writing – review & editing.

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2023.103497>.

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