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Optimizing CO_2 transfer in algal open ponds

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ABSTRACT

The objective of this study was to optimize the CO_2 injection system of algal raceway open ponds to minimize CO_2 losses to the atmosphere and therefore reduce operational costs. CO_2 transfers can be optimized by increasing the bubble-to-culture CO_2 transfer rate and by decreasing the culture-to-atmosphere CO_2 transfer rate. CO_2 transfer coefficients were first experimentally determined on a pilot-scale algal pond for different designs of the injection system. The impact of five design parameters was tested: the CO_2 diffuser length, the CO_2 diffuser position, the CO_2 flow rate, the paddle wheel rotation speed and the water level. Culture-to-atmosphere transfer coefficient was only significantly impacted by the paddle wheel rotation speed (range: 3.42–48.7 10^{-3} min^{-1}; base-case value: 17.1 10^{-3} min^{-1}). Bubble-to-culture transfer coefficient, determined for a mix of fine and coarse CO_2 bubbles, varied significantly with the CO_2 injection flow rate (range: 1.47–18.3 10^{-4} min^{-1}; base-case value: 9.11 10^{-4} min^{-1}) and water level (range: 7.46–14.4 10^{-4} min^{-1}). The efficiencies of the various system designs at full-scale were then extrapolated through simulation by coupling an algal productivity model to the CO_2 transfer model developed in this study. Reducing the water level from 0.2 m down to 0.1 m reduced CO_2 supply by 14%. Reducing the paddle wheel rotation speed from 21 rpm to 13 rpm decreased CO_2 supply by 40%. Increasing the pH set point from 7.2 to 8 reduced CO_2 supply by 38% but also decreased *Dunaliella salina* biomass productivity by 17%. A trade-off must be achieved between high biomass productivity and lower environmental footprint.

1. Introduction

While biofuels from microalgae are considered as a potential alternative to fossil fuels, the cost-efficiency of the process is still under study [1,2]. Current estimations based on large scale extrapolation place the cost of biofuels from microalgae between 2.8 and 3.7 USD·L^{-1} [3,4]. The variations across studies are mostly due to assumptions regarding productivity predictions, system operation and assumptions regarding various costs [5]. As this relatively high price makes algal biofuels non-competitive with fossil fuels, recent studies aimed to improve algal productivity by optimizing system design and operation. For example, Béchet et al. [6] optimized the water level and hydraulic retention time to maximize algal productivity while reducing water demand. Putt et al. [7] optimized the CO_2 injection system by adding a carbonation column. The use of flue gases or wastewater were also studied to maximize algal productivity while decreasing nutrients demand [6–9].

CO_2 is often considered as a free resource in technico-economic assessments of full-scale algal production whereas CO_2 injection costs were reported to represent up to 27% of algal production costs [9]. These costs are particularly high in open systems as a non-negligible fraction of injected CO_2 is lost in the atmosphere through gas transfer. For example, Doucha and Lívanský [10] showed that only 45.3% of CO_2 injected in an algal pond was absorbed by the algae, the rest being lost in the atmosphere. Only few studies aimed to quantify the impact of the pond design on the CO_2 transfer rates. Such characterization is however crucial for system optimization. Within this context, the objective of this study was to optimize the design of the CO_2 injection system of algal open ponds to minimize CO_2 losses and therefore reduce operational costs. CO_2 transfer rates were therefore first experimentally determined for different designs of the CO_2 injection system of a pilot-scale open pond. The efficiency of these different designs at reducing CO_2 losses was then quantified through simulations by coupling an algal productivity model to the CO_2 transfer model developed in this study.

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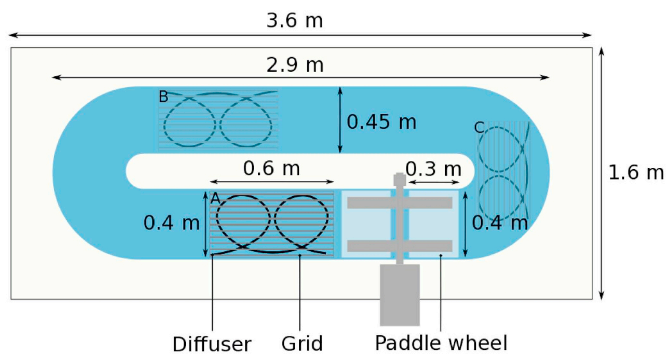

Fig. 1. Raceway pond and CO_2 diffusion system in the base-case (see Table 1 for details) - A, B, and C represent the position of the diffuser (A: downstream position (base-case); B: opposite position; C: upstream position).

2. Materials and methods

2.1. System design

The pilot fiber-glass raceway pond used in this study (surface area: 2.61 m^2; depth: 25 cm; Fig. 1) was equipped with a stainless steel paddle wheel (with 4 paddles) to ensure homogenous mixing. CO_2 was bubbled into the pond through a microporous tube (*Aqua Flow A2000*) maintained at the pond bottom by a stainless steel grid.

2.2. Possible variations in set-up parameters

Various design parameters can be modified to minimize CO_2 losses, which are due to two distinct mechanisms. First, a fraction of the CO_2 bubbles injected at the pond bottom reaches the pond surface before dissolving into the culture. Higher bubble-to-culture CO_2 transfer rates can therefore contribute to minimize CO_2 losses. Secondly, as CO_2 concentration in the pond often exceeds the equilibrium concentration with the atmosphere, CO_2 tends to transfer from culture to the atmosphere [11]. Decreasing culture-to-atmosphere CO_2 transfer rates would therefore reduce CO_2 losses. The following five parameters can theoretically be optimized to minimize CO_2 losses:

- The **CO_2 diffuser length**: bubble-to-culture transfer rates are theoretically proportional to the bubbles surface area, and therefore to the size and density of bubbles [12,13]. As the diffuser length influences the number of bubbles within the medium, this parameter was made vary between 2 m and 4 m (base-case value of 3 m).
- The **CO_2 diffuser position**: The bubble retention time (i.e. the amount of time that bubbles remain in the culture before reaching the pond surface) theoretically depends on the diffuser position. For example, relative positions of the paddle wheel and CO_2 diffuser may impact bubbles trajectories, hence bubble retention time. Diffuser position may therefore influence the bubble-to-culture transfer rate as a longer bubble retention time means a higher rate of CO_2 transfer from bubbles to culture medium [14]. Three different positions were selected for the CO_2 diffuser: upstream of the paddle wheel, downstream of the paddle wheel (base-case position) and at the opposite position of the paddle wheel (Fig. 1).
- The **CO_2 flow rate**: The CO_2 flow rate impacts the bubbles density and therefore the bubble-to-culture transfer rate. The following calculations were performed to estimate the range of relevant values for the CO_2 flow rate. The maximum CO_2 flow rate theoretically needed in this algal pond was determined from the maximum light intensity that can reach an outdoor pond (approximately 1000 $W{\cdot}m^{-2}$). As 45% of this radiation is photosynthetically active [15] and based on a conservative assumption of a photosynthetic efficiency of 6.56% [16], a heat value of 17.5 $kJ{\cdot}g^{-1}$ [17], a carbon content of 50% [18], and a CO_2 injection efficiency of 55% [10], the maximum CO_2 flow rate tested in this study was 0.67 $L{\cdot}min^{-1}$. The minimal CO_2 flow rate was set at 0.05 $L{\cdot}min^{-1}$ and the mid-value 0.36 $L{\cdot}min^{-1}$ was used as a base-case value.
- The **paddle wheel rotation speed and related flow speed**: The paddle wheel rotation speed impacts the level of turbulence at the pond surface and the transfer at the paddle wheel [19]. This design parameter should therefore impact the culture-to-atmosphere transfer rate [20]. Minimum and maximum paddle wheel rotation speeds of 13 rpm and 29 rpm were selected in this study, 21 rpm being used as a base-case value (these values were observed to ensure homogeneous mixing in the pond without causing mechanical stress on the algal cells [21]). The following relationship exists between the rotation speed of the paddle wheel (*RPM*, in rpm) and the flow speed (v, in $m\,s^{-1}$):

$$v = \frac{2r\pi}{60} RPM \qquad (1)$$

where r is the radius of the paddle wheel (m).

Based on Eq. (1), the flow speeds at the paddle wheel should theoretically be 0.66, 0.91 and 0.44 $m{\cdot}s^{-1}$ for the base-case, high and low paddle wheel rotation speeds, respectively. However, as the flow speed decreases as the water flows in the pond channels, the average flow speed is expected to be lower than these values.

- The **water level**: Water level impacts the bubble retention time and should therefore impact the bubble-to-culture CO_2 transfer rate. Minimum and maximum water levels of 0.1 m and 0.2 m were selected in this study; 0.15 m being used as a base-case value.

A total of eleven experiments were carried out to quantify the impact of each of these five design parameters on the CO_2 transfer rates. Transfer rates were first measured in the base-case when parameters were all set at their base-case values (Table 1). CO_2 transfer rates were then measured when all parameters were set at their base-case values apart from one parameter set at either its high or its low value (Table 1). For example, to estimate the impact of the high water level on CO_2 transfer rates, the CO_2 flow rate, the diffuser length and position, and the paddle wheel rotation speed were set at their base-case values (0.36 $L{\cdot}min^{-1}$, 3 m, 'downstream of the paddle wheel', 21 rpm, respectively), the water depth was set at its high value (0.2 m).

2.3. Determination of CO_2 transfer coefficients

This section details how the two rates of CO_2 transfer were experimentally determined (i.e. from bubbles to culture and from culture to atmosphere). In each experiment, the pond was first filled with seawater up to the desired water level as listed in Table 1. The paddle wheel was started and CO_2 injection began once pH was steady, resulting from equilibrium with atmospheric CO_2 (Material used: InPro 4881i glass pH probe; Data logger: Mettler Toledo M300). CO_2 injection was stopped after 20–30 min and pH was monitored for several additional hours to record the increase of pH over time.

Table 1
System design parameters and their values.

Parameters tested	Base-case	High	Low
CO_2 flow rate ($L{\cdot}min^{-1}$)	0.36	0.67	0.05
Water depth (m)	0.15	0.2	0.1
Diffuser length (m)	3	4	2
Diffuser position	Downstream of the paddle wheel	Upstream of the paddle wheel	At the opposite of the paddle wheel
Paddle wheel rotation speed (rpm)	21	29	13