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Demonstration of direct air capture of CO_2 using microalgae raceway reactors

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ABSTRACT

The continuous increase in atmospheric CO_2 concentration underscores the urgent need for scalable and energy-efficient carbon removal technologies. This study demonstrates, for the first time, the implementation of a tailored Direct Air Capture (DAC) concept integrated within large-scale microalgae raceway reactors, enabling direct CO_2 uptake from ambient air without external gas supply. A 600 m^2 reactor operated continuously with Scenedesmus sp. maintained stable productivity (12 g m^{-2} day^{-1}) under extreme carbon limitation (TIC ≈ 20 mg L^{-1}, pH ≈ 10). Fine-bubble aeration in the sump achieved nearly complete CO_2 removal from air streams, while passive absorption across the raceway and paddlewheel sections provided almost all the carbon required for biomass growth. The overall CO_2 removal efficiency reached 95%, confirming the reactor's operation as a functional bio-DAC system. The estimated energy demand for air bubbling (≈ 2.9 kWh kg^{-1} CO_2) is comparable to or below that of current engineered DAC technologies. This approach establishes a low-cost, renewable-compatible, and scalable pathway for atmospheric CO_2 capture that couples negative-emission performance with biomass production, laying the groundwork for decentralized, carbon-negative biotechnological systems contributing to global greenhouse-gas mitigation.

1. Introduction

The continuous rise in global temperature caused by greenhouse gas emissions, particularly CO_2, demands effective strategies to mitigate their impact. Conventional measures—such as improving combustion efficiency, reducing fossil fuel use, and implementing Carbon Capture and Storage (CCS)—help limit future emissions but cannot remove CO_2 already accumulated in the atmosphere [1]. Hence, increasing attention is given to Negative Emission Technologies (NETs), including Direct Air Capture (DAC), which can actively extract CO_2 from air [2,3]. As noted by Sandalow et al. [4], NET portfolios should integrate both engineered and biological solutions, with algal DAC systems offering additional benefits in energy integration and land use.

Direct Air Capture (DAC) relies on a range of physicochemical separation processes to selectively isolate CO_2 from ambient air, including liquid solvent absorption systems based on alkaline solutions or amines, solid adsorbent–based technologies employing porous or functionalized materials, and more recently membrane-based separation processes using polymeric or facilitated-transport membranes designed to operate under atmospheric CO_2 concentrations [2,3,5–7]. Additional approaches, such as electrochemical DAC exploiting pH- or redox-swing mechanisms, are also emerging as potentially lower-temperature alternatives [8]. Despite significant technological progress, all engineered DAC routes remain constrained by high energy demand, regeneration requirements, and material costs, which currently limit large-scale deployment and motivate the exploration of biologically integrated alternatives [9].

However, recent studies demonstrate that coupling DAC with bio-based CO_2 utilization can markedly reduce energy demand and operational costs through process integration [10,11], reinforcing its role as a key technology for achieving net-negative emissions and long-term climate mitigation. Moreover, techno-economic analyses indicate that

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the large-scale deployment of DAC remains constrained by high energy requirements and material costs, with current capture estimates exceeding 300 USD t^{-1} CO_2 [6,7,12]. These challenges highlight the need for low-energy, bio-assisted DAC solutions that leverage renewable energy and natural absorption mechanisms.

Microalgae are photosynthetic microorganisms renowned for their high capacity to fix carbon dioxide (CO_2). Stoichiometrically, approximately 1.8 kg of CO_2 is required to produce 1 kg of microalgal biomass. Considering that large-scale systems can achieve productivities of up to 100 tons ha^{-1} yr^{-1} , the corresponding CO_2 fixation potential can reach 200 tons ha^{-1} yr^{-1} , ranking microalgae among the most efficient biological systems for carbon capture [13,14]. Traditionally, microalgae production relies on pure CO_2 or CO_2-enriched gas streams derived from combustion or fermentation processes. Under these conditions, the high CO_2 concentration and its relatively high solubility in water promote rapid transfer into the culture medium. Nevertheless, even when using concentrated gas sources, maintaining efficient gas–liquid mass transfer remains a major operational challenge [15]. To address this limitation, numerous studies have explored engineering strategies such as gas recirculation, optimized sump design, and the use of closed or hybrid photobioreactor configurations to enhance carbonation efficiency [16–18]. These advances are essential for enabling the reliable and scalable application of microalgae as a sustainable CO_2 capture and utilization technology. Recent reviews further emphasize that the CO_2 fixation potential of microalgae depends not only on species selection but also on process optimization, where mass transfer and pH control remain the main rate-limiting steps for large-scale deployment [19].

A major challenge in advancing microalgae-based carbon capture technologies lies in enabling these systems to effectively remove CO_2 directly from ambient air, where concentrations are extremely low (~420 ppm) and gas–liquid mass transfer is inherently limited [1]. Achieving this goal requires transforming conventional production systems into functional Direct Air Capture (DAC) units that can operate autonomously, without dependence on external CO_2 sources. Among the available reactor designs, open raceway ponds stand out as the most promising due to their simple construction, low capital cost, and proven scalability for large-area deployment. Raceway algal pond systems have demonstrated stable operation at large scale for wastewater and CO_2 capture applications, confirming their robustness and adaptability under variable outdoor conditions [20]. Their extensive surface exposure to the atmosphere naturally facilitates gas exchange—both oxygen release and CO_2 absorption—but the overall efficiency of this process depends strongly on factors such as hydrodynamics, temperature, solar irradiance, and, particularly, pH.

Alkaline conditions can substantially increase the absorption of atmospheric CO_2 by shifting the carbonate equilibrium toward bicarbonate and carbonate species, thereby maintaining a concentration gradient that favors gas transfer [21]. Nevertheless, because the gas–liquid mass transfer coefficient (K_la) for CO_2 under ambient conditions is typically very low, the flux of CO_2 from air alone is generally insufficient to sustain high biomass productivities. To overcome this limitation, many large-scale raceways incorporate auxiliary units such as sumps or “degasser” sections, where gas–liquid contact is intensified through bubbling or mechanical agitation [22]. These sumps are primarily designed to remove excess dissolved oxygen—a common issue in dense cultures—but have also proven effective in improving CO_2 transfer when concentrated gas streams or flue gases are supplied [23]. However, their potential role as passive air–liquid contactors for capturing CO_2 directly from the atmosphere has not yet been systematically investigated, representing a critical knowledge gap that this study seeks to address.

In this study, we investigate the potential of open raceway pond reactors to function as integrated systems for Direct Air Capture (DAC) of CO_2 directly from the atmosphere. The analysis focuses on quantifying CO_2 transfer dynamics and establishing the complete CO_2 mass balance in a 600 m^2 pilot-scale reactor operated continuously under outdoor conditions, where ambient air served as the sole carbon source for microalgal growth. Particular attention is given to evaluating how key operational parameters—such as pH and airflow rate—affect both the reactor’s capacity to absorb CO_2 from the air and its ability to meet the biological carbon requirements of the microalgae population. By combining experimental measurements with mass transfer modeling, this work identifies the operational thresholds and reactor design features necessary to sustain biomass productivity under carbon-limited conditions. The results presented are derived from real-environment operation, providing one of the first quantitative demonstrations of large-scale microalgae production driven exclusively by atmospheric CO_2. The findings not only validate the technical feasibility of this approach but also support the optimization and upscaling of the patented CHLYDRO technology (WO2024245917), designed to enable decentralized and energy-efficient CO_2 removal. Ultimately, this research contributes to the development of autonomous, low-cost biotechnological platforms capable of achieving net-negative carbon emissions in remote or off-grid regions, positioning microalgae-based DAC as a viable component of global carbon mitigation strategies.

2. Materials and methods

2.1. Microorganism and culture medium

The raceway was inoculated with the microalgae strain *Scenedesmus* sp. This particular strain was chosen for its resilience and adaptability, as it is highly tolerant of fluctuating growth conditions and resistant to common contaminations and grazers. The assays were conducted using a specific culture medium, known as Mann & Myers medium. This medium was prepared with reclaimed water and supplemented with a precise mix of fertilizers (0.9 $g \cdot L^{-1}$ $NaNO_3$, 0.14 $g \cdot L^{-1}$ $KH_2(PO_4)$, 0.18 $g \cdot L^{-1}$ $Mg(SO_4)_2$ and 0.02 $g \cdot L^{-1}$ Karentol (Konegard, Spain)). The inoculum for the reactor was produced in a parallel raceway reactor of 100 m^2 operated in continuous mode using freshwater and fertilizers following the same recipe as before. The inlet reclaimed freshwater exhibited an initial dissolved inorganic carbon concentration of 100 mg L^{-1} at pH 8.0–8.2.

2.2. Raceway reactors

The experiments were conducted in a 600 m^2 raceway reactor located at the "CIESOL" Research Centre in Almería, Spain (36° 48′N–2° 43′W) (Fig. 1). The reactor design includes four channels, each 38 m long, 4 m wide, and 0.46 m high. The total culture volume is 105 m^3 , which is circulated through a 6.3 m^3 sump located 2 m into one of the channels. The sump itself has a diameter of 2 m and is 2 m deep. A comprehensive monitoring and control system was implemented to manage the reactor's key parameters. Probes for culture pH, temperature, and dissolved oxygen (DO) were connected to a control-transmitter unit (MM44) from Crison Instruments. The DO probe was specifically positioned at the end of a channel, just before the paddlewheel, to capture the most significant daily fluctuations. CO_2 probes from Vaisala were used to monitor the atmospheric gas and the gas outlet from the sump (Indigo, Vaisala). Data from these probes, along with a mass flow meter (PFM 725SF01-F, SMC) for measuring air flow, were managed by DAQFactory software.

Air was supplied to the reactor at a 300 mbar overpressure using a blower. This air was delivered through fine bubble diffusers (AFT2100, ECOTEC), which produced bubbles with a diameter smaller than 2 mm and an estimated residence time of 5–10 s within the sump. Notably, neither the pH nor the temperature of the culture was actively controlled during the experiments. A Supervisory Control and Data Acquisition (SCADA) system, based on a distributed architecture, enabled real-time monitoring and control. This system integrated all the sensors for culture monitoring as well as meteorological inputs like solar radiation, air temperature, and wind speed. All sensors sampled data every 10 s, allowing the system to detect rapid process fluctuations and support

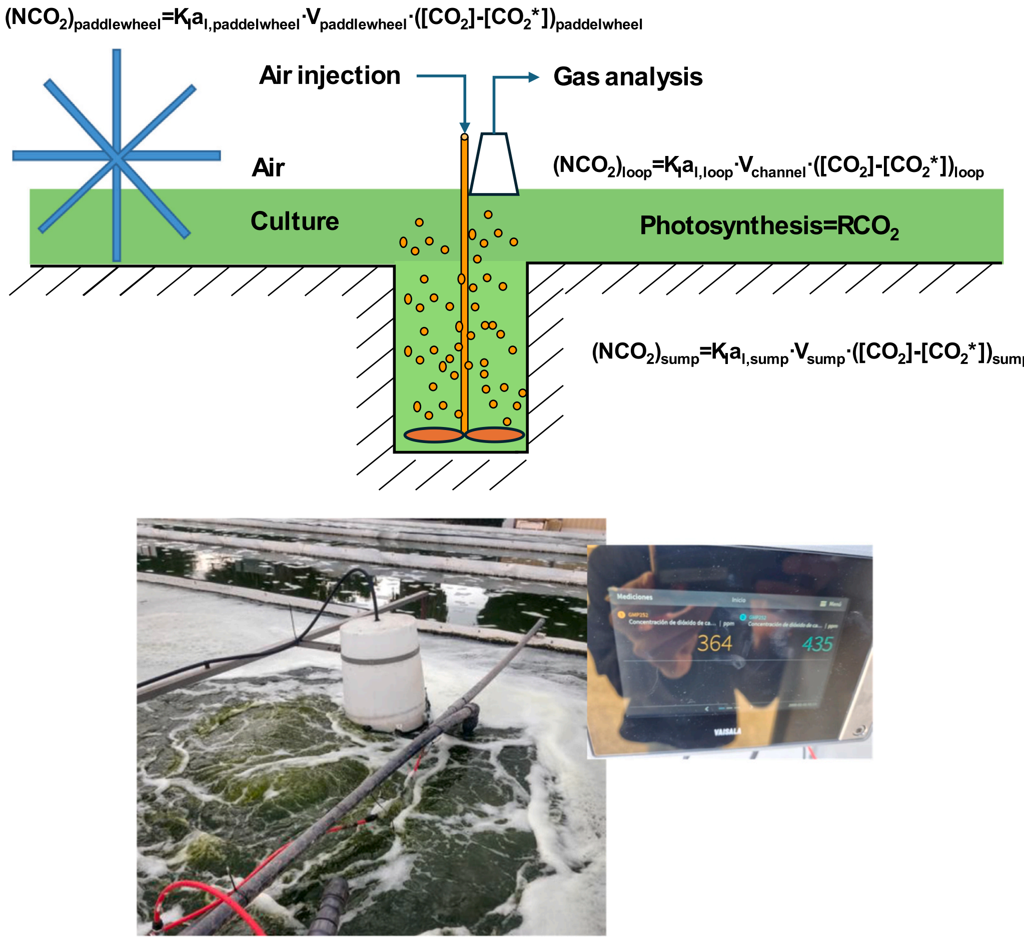

Fig. 1. Schematic representation of the experimental setup used in this study (top), showing the main reactor elements and air–liquid contact zones, and photograph of the 600 m² raceway reactor operating under outdoor conditions (bottom).

adaptive control strategies. Data were managed by a central control unit and visualized via a human-machine interface (HMI) for remote supervision and alarm management [24].

The raceway reactor was operated at a constant culture depth of 0.15 m in a semi-continuous mode. A fixed dilution rate of 0.2 day^{-1} was applied to maintain a target biomass concentration of 0.8 g/L, although the final biomass concentration was lower, ranging from 0.4 to 0.6 g/L. To achieve this, a portion of the biomass was harvested daily, and fresh medium was added to the reactor. The daily addition of freshwater compensated for evaporative losses. Biomass concentration was measured every morning before harvesting. This was done by filtering 40 mL aliquots of the culture through a pre-dried 0.45 µm filter (Macherey-Nagel). The filters were then dried in an oven at 80°C for 24 h to determine the dry weight. The nutrient content of the culture supernatant was also evaluated daily to ensure that nutrient limitations did not occur, and fertilizers were added as needed. Total inorganic carbon (TIC) was determined on filtered culture samples by acidification to convert all inorganic carbon species into CO_2, followed by quantification of the released CO_2 using a Shimadzu TIC analyzer, according to standard analytical procedures.

2.3. Mass transfer and mass balance into the reactor

The CO_2 mass transfer and overall carbon balance in the raceway reactor were determined following the methodology described by Arraga et al. [25], adapted to the specific configuration of the present system. The approach combines experimental determination of local mass transfer coefficients (K_la) with theoretical estimation of the driving force for CO_2 exchange between the culture broth and the surrounding air, considering the physicochemical equilibrium of the carbonate system and the culture pH.

In open raceway reactors, CO_2 transfer between the gas and liquid phases occurs simultaneously in several sections of the system: (i) the sump, where air bubbling enhances gas–liquid contact through fine bubbles; (ii) the paddlewheel region, characterized by high turbulence and surface renewal; and (iii) the open channel, where diffusion and convective exchange with the atmosphere dominate. Each of these zones contributes differently to the total CO_2 flux depending on hydrodynamic conditions, interfacial area, and local chemical equilibrium. The mass transfer rate of CO_2 (r_{CO_2}) in each section was expressed by Eq. 1, where K_La(s^{-1}) is the overall volumetric mass transfer coefficient, $C^*_{CO_2}$(mg L^{-1}) is the equilibrium CO_2 concentration corresponding to the partial pressure of CO_2 in air, and C_{CO_2}(mg L^{-1}) is the actual dissolved CO_2 concentration in the culture broth. The latter was determined from the total inorganic carbon (TIC) concentration and the relative distribution of carbonate species, which depend on the culture pH and temperature. The equilibrium concentration of CO_2 in water was calculated using Henry's law (Eq. 2) where $H_{CO_2}$is the Henry constant (mol m^{-3} Pa^{-1}) corrected for temperature, and $p_{CO_2}$is the partial pressure of CO_2 in the gas phase (typically 400 ppm). The instantaneous $C_{CO_2}$was obtained from the measured TIC and pH, using the carbonate equilibrium constants K_1 and $K_2$for the dissociation of carbonic acid, according to Eq. 3. The volumetric mass transfer coefficients (K_la) for each section were determined experimentally from oxygen desorption and absorption tests following Arraga et al. [25]. The coefficients were adjusted for the respective diffusivities of the gases in water, using the ratio of diffusion coefficients (D_{CO_2}/D_{O_2})^0.5. Paddlewheel and channel exhibit constant K_La values of 160 and 1 h^{-1}, respectively, whereas the value into the sump is a function of air flow rate, values up to 208 h^{-1} being measured at maximum of 500 L/min.

$$N_{CO_2} = K_L a \cdot (C^*_{CO_2} - C_{CO_2}) \quad (1)$$

$$C^*_{CO_2} = H_{CO_2} \cdot p_{CO_2} \quad (2)$$

$$C_{CO_2} = \frac{TIC}{1 + \frac{K_1}{[H^+]} + \frac{K_1 K_2}{[H^+]^2}} \quad (3)$$

The overall CO_2 balance for the system was then established as the sum of all gaseous and aqueous fluxes, including biological production/consumption by respiration/photosynthesis during night and daylight periods. This was estimated from dissolved oxygen measurements following the methodology proposed by [25]. Positive values denote CO_2 inputs (absorption or respiration), and negative values denote CO_2 removal (photosynthetic fixation or degassing). The CO_2 released by respiration was estimated indirectly from nighttime dissolved oxygen consumption rates, assuming aerobic respiration and a respiratory quotient close to unity, thereby allowing conversion of oxygen uptake into equivalent CO_2 production. The volumetric gas–liquid mass transfer coefficients (K_La) for the paddlewheel and open-channel sections were obtained from experimental oxygen transfer measurements performed in the same raceway configuration and subsequently scaled to CO_2 using diffusivity-based correlations. Chemical enhancement of CO_2 absorption was not explicitly included in the K_La values, as under atmospheric CO_2 concentrations the overall uptake rate is primarily governed by physical mass transfer, while the effect of carbonate chemistry is accounted for through the pH-dependent driving force expressed in terms of dissolved inorganic carbon.

3. Results and discussion

For clarity, this section is structured to clearly distinguish between results derived from theoretical calculations and mass balance modelling, and those obtained from experimental operation of the large-scale raceway reactor.

3.1. Theoretical CO_2 demand and carbon balance in large-scale raceway reactors

This subsection presents results derived from stoichiometric calculations and mass balance modelling. To analyze the potential of microalgae for direct air capture processes, it is important to fix the boundary conditions for this process on a large scale. Thus, in microalgae production systems, CO_2 is supplied both to maintain the culture pH within the optimal range and to provide the inorganic carbon required for photosynthesis, considering that approximately 45% of the dry biomass corresponds to carbon assimilated from the supplied CO_2. Under typical outdoor conditions, biomass productivities in open raceway ponds range from 10 to 25 g m^{-2} day^{-1}, although optimized systems operated in warm climates and with efficient mixing can achieve values up to 40 g m^{-2} day^{-1} [14,26]. The CO_2 utilization efficiency—defined as the fraction of supplied carbon actually fixed into biomass—typically lies between 30% and 60%, depending on reactor design, mixing intensity, and pH control, with higher efficiencies obtained under optimized gas transfer and recirculation conditions [17,27]). However, by implementing advanced monitoring and control strategies, such as model-based pH regulation and adaptive CO_2 dosing, carbon utilization efficiencies close to 100% can be achieved, ensuring nearly complete assimilation of the injected CO_2 [28]. Comparable improvements in process efficiency have been observed in microalgae–wastewater systems where advanced nutrient and pH control strategies were implemented [29]. The unit cost of CO_2 supply for large-scale microalgae production generally averages around €150 per ton CO_2, representing one of the major operational expenses (Acién et al., 2017).

These figures are relevant because they determine the boundary conditions for CO_2 supply in microalgae reactors. Thus, for a raceway reactor with a surface area of 600 m^2, and assuming a biomass productivity between 10 and 25 g m^{-2} day^{-1}, the theoretical CO_2 consumption—calculated using the stoichiometric ratio of 1.8 kg CO_2 per kg biomass—ranges from 10.8 to 27.0 kg CO_2 day^{-1} (Fig. 2). The CO_2 demand was calculated on a dry biomass basis, assuming a typical carbon content of microalgal biomass of 45–50% (w/w), which corresponds to an equivalent fixation of approximately 1.8 kg CO_2 per kg of dry biomass. When considering CO_2 utilization efficiencies between 30% and 100%, the actual CO_2 supply required to sustain biomass growth increases significantly. For instance, at a productivity of 25 g m^{-2} day^{-1}, the effective CO_2 input would vary from 27 kg CO_2 day^{-1} at full utilization to 225 kg CO_2 day^{-1} at 30% efficiency. This translates into a carbon supply cost ranging from €0.27 to €2.25 per kg of biomass. This wide variability underscores the critical influence of CO_2 utilization efficiency on both the carbon footprint and economic performance of microalgae production. Because CO_2 represents a substantial share of the total operating cost, inefficient utilization can significantly increase the final biomass cost and reduce process sustainability.

3.2. Expected CO_2 exchange with the atmosphere under alkaline conditions

The following analysis is based on theoretical equilibrium and mass transfer considerations. To satisfy the carbon requirements of the culture, CO_2-rich gases are typically supplied to microalgae reactors; however, the dissolved inorganic carbon (DIC) already present or introduced with the culture medium also makes a relevant contribution. This inorganic carbon, mainly in the form of bicarbonate and carbonate ions, participates in the bicarbonate buffer system, which regulates both the concentration of dissolved CO_2 and the equilibrium with atmospheric CO_2. The dissolved inorganic carbon (DIC) supplied with the culture medium does not originate from equilibrium with atmospheric CO_2, but from the natural alkalinity and inorganic carbon content of the freshwater used, which, under the alkaline operating conditions of the reactor (pH $\approx$ 10), is predominantly stored as bicarbonate and carbonate species, leading to DIC levels substantially higher than those attainable in freshwater equilibrated with air. Depending on the pH of the culture, the dissolved CO_2 concentration may be higher or lower than the equilibrium value with the atmosphere, leading either to CO_2 stripping or CO_2 absorption. From a chemical perspective, CO_2 capture in alkaline microalgae raceway reactors is governed by the carbonate–bicarbonate equilibrium of the culture medium, which effectively acts as a dynamic absorbent system. At elevated pH, dissolved CO_2 is rapidly converted into bicarbonate and carbonate species, lowering the free CO_2 concentration in the liquid phase and maintaining a strong driving force for continuous absorption of atmospheric CO_2. This absorbed inorganic carbon is subsequently consumed by photosynthesis, thereby regenerating the absorbent capacity of the medium in situ. In contrast to conventional DAC systems relying on external sorbents, this biologically assisted mechanism couples CO_2 absorption, regeneration, and utilization within a single process, with gas–liquid contact zones such as the sump, paddlewheel, and open channels enhancing mass transfer efficiency.

At low pH values ($<$ 9), a significant fraction of inorganic carbon exists as dissolved CO_2 and carbonic acid, producing a positive gradient of CO_2 partial pressure between the culture and the air. Under these conditions, the reactor behaves as a CO_2 emitter, losing carbon mainly through stripping in the open channels and turbulence zones such as the paddlewheel. In the present case, at pH 8, the theoretical CO_2 demand for biomass synthesis (21 kg day^{-1}) increased to 52 kg day^{-1} due to stripping losses of 18 kg day^{-1} in the channel and 23 kg day^{-1} at the paddlewheel, while only 11 kg day^{-1} was supplied with the culture

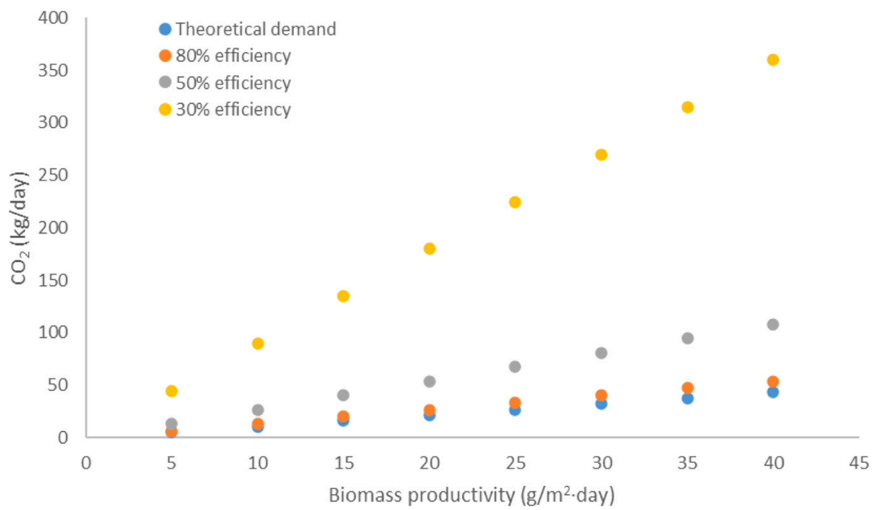

Fig. 2. Influence of biomass productivity and CO_2 utilization efficiency on the CO_2 consumption of the 600 m^2 raceway reactor.

medium (Fig. 3). Conversely, at high pH values (> 11), most inorganic carbon is converted into bicarbonate and carbonate species, resulting in almost negligible free CO_2 concentrations in the liquid. The partial pressure of CO_2 in the culture becomes lower than that in the atmosphere, thereby promoting passive CO_2 absorption from the air. At pH 10, the net CO_2 demand was reduced to 7.4 kg day^{-1} , since atmospheric absorption reached 1.6 kg day^{-1} in the channel and 2.1 kg day^{-1} at the paddlewheel, while 10.6 kg day^{-1} was still provided with the culture medium (Fig. 3). Although pH values above 11 are discussed here as a theoretical upper limit for maximizing atmospheric CO_2 absorption, such conditions are generally unfavorable for microalgal growth, as they strongly limit CO_2 availability and nutrient bioavailability and can induce physiological stress; accordingly, the reactor in this study was operated at lower pH values (≈9.7–10.2) compatible with stable growth of Scenedesmus spp.

Overall, the results highlight that the pH-dependent carbonate equilibrium governs the direction and magnitude of CO_2 fluxes in raceway reactors. At lower pH values, CO_2 stripping dominates, substantially increasing the apparent CO_2 demand, whereas at higher pH values, bicarbonate buffering and atmospheric absorption mitigate carbon losses. These findings confirm that pH is critical to minimize CO_2 emissions and optimize carbon utilization efficiency in large-scale open raceway systems [23,30,31]. This agrees with previous studies showing that pH not only regulates carbonate equilibria but also affects nutrient availability and overall reactor performance [32,33], underscoring the importance of pH control for maintaining both CO_2 capture and biomass productivity.

3.3. *Experimental performance of the 600 m^2 raceway reactor under DAC operation*

This subsection reports experimental results obtained during continuous operation of the 600 m^2 raceway reactor. The pH also plays a critical role in determining the biomass productivity of microalgae cultures. Most microalgae species exhibit optimal growth under near-neutral to slightly alkaline conditions (pH 7–8.5), beyond which growth rates progressively decline. At higher pH values, above 9.5, both CO_2 availability and nutrient solubility decrease, limiting photosynthetic carbon fixation and thereby reducing productivity. When no external CO_2 is supplied—or under severe CO_2-limiting conditions—the pH of the culture tends to rise naturally until a balance is reached between CO_2 supply from the atmosphere and CO_2 consumption by photosynthesis. In the case of *Scenedesmus* sp. cultivated in the 600 m^2 raceway reactor, the pH increased to values of 10.0, leading to a reduction in biomass productivity to approximately 12 g m^{-2} day^{-1}- (Fig. 4). Under these conditions, the theoretical CO_2 demand

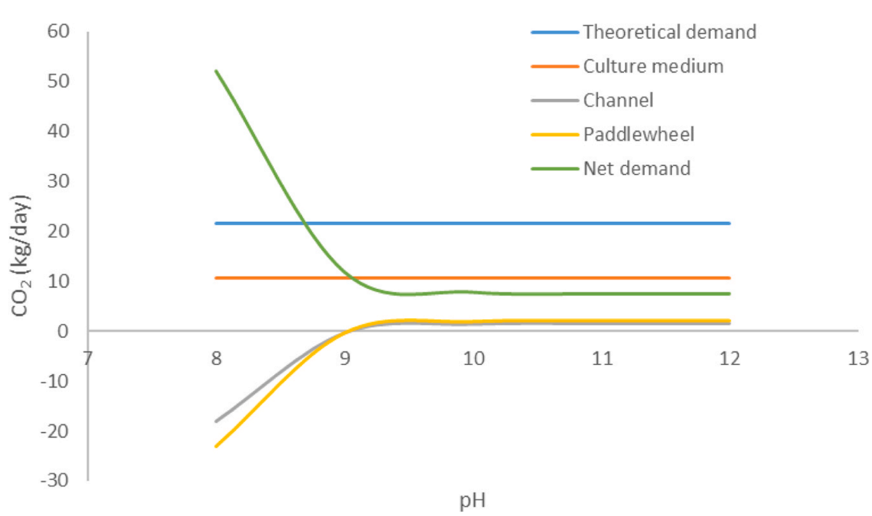

Fig. 3. Effect of pH on the modeled CO_2 exchange with the atmosphere in the different reactor sections (channel, paddlewheel, and sump) and on the overall CO_2 balance of the 600 m^2 raceway reactor.

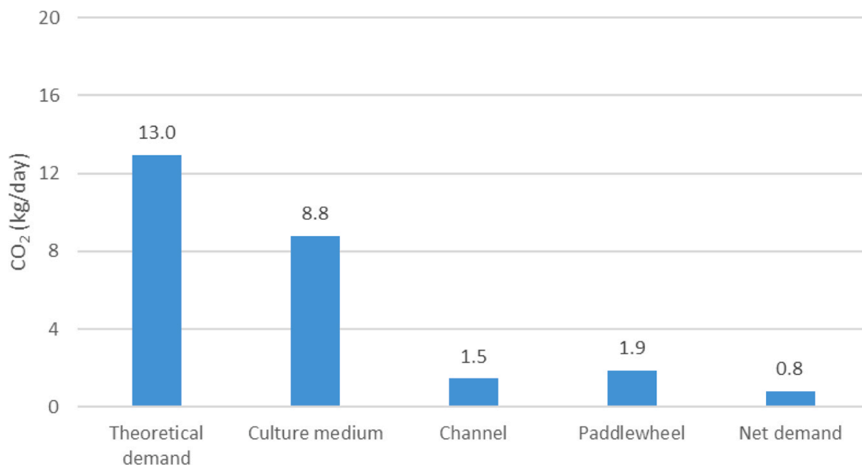

Fig. 4. CO_2 supply–demand analysis for the 600 m^2 raceway reactor operated at an average bulk pH of 10 and a biomass productivity of 12 g m^{-2} day^{-1} , showing the relative contributions of atmospheric absorption and dissolved inorganic carbon.

corresponding to this productivity is 13.0 kg CO_2 day^{-1} . This demand is partially met by the inorganic carbon (DIC) already present in the culture medium, contributing with 8.8 kg CO_2 day^{-1} . In addition, natural atmospheric absorption provides a small but relevant contribution, with 1.5 kg CO_2 day^{-1} absorbed across the open channel and 1.9 kg CO_2 day^{-1} through the paddlewheel region. Altogether, these sources account for 12.2 kg CO_2 day^{-1} , leaving a net external CO_2 requirement of 0.8 kg day^{-1} to sustain the observed productivity. To meet this unmet demand, different CO_2 sourcing strategies can be considered.

The use of pure CO_2 is the most common approach in high-value biomass production due to its precise control and reliability [34], but it involves high operational costs and depends on a consistent logistics chain for gas delivery—often impractical for decentralized or remote sites. Alternatively, the use of industrial flue gases represents a more sustainable and environmentally beneficial option, simultaneously contributing to greenhouse gas mitigation through flue gas valorization [35]. Nevertheless, this approach imposes spatial and infrastructural constraints, as reactors must be located near emission sources equipped with suitable gas-cleaning systems. A third and increasingly attractive alternative is the direct air capture (DAC) of atmospheric CO_2, which can be seamlessly integrated with open microalgae systems [11,36]. Similar biological DAC approaches have been proposed by Singh and Saxena [37], who demonstrated that coupling atmospheric CO_2 absorption with biomass production can reduce capture costs and enhance overall process sustainability through integrated bioenergy systems. Based on the CO_2 concentration in ambient air, approximately 700 L·min^{-1} of air would need to be processed to extract the 0.8 kg CO_2 day^{-1} required in this case.

Moreover, enhancing CO_2 input from ambient air would not only lower the culture pH but also increase biomass productivity, thereby improving the overall CO_2 capture efficiency of the system. While DAC offers the advantage of site independence and aligns with long-term carbon neutrality goals, its technical maturity and energy costs remain significant challenges, especially for large-scale implementation. This comparative evaluation emphasizes that the choice of CO_2 source is not only a technical decision but also one that profoundly impacts production costs, operational logistics, and environmental footprint. Tailoring the CO_2 supply strategy to the scale, location, and economic goals of the production system is thus essential for maximizing efficiency and sustainability.

Direct Air Capture (DAC) technologies, regardless of the specific approach, inherently require significant energy input and capital investment in infrastructure. This is due to the fundamental challenge of separating CO_2 from atmospheric air, where its concentration is extremely low—approximately 0.8 g CO_2 per cubic meter of air. Among the most widely explored and potentially scalable DAC technologies are selective membrane systems and adsorption/desorption processes using solid or liquid sorbents. These technologies are currently considered among the most promising in terms of selectivity and efficiency, yet they remain complex and costly, largely because of the energy required for regeneration and gas compression, as well as the materials and maintenance demands of the systems involved. An alternative and more integrated approach to DAC involves utilizing the existing architecture of raceway reactors, particularly the sump section, as a functional CO_2 absorber. If properly designed and operated, the sump can serve as an effective air–liquid contact zone for CO_2 absorption from ambient air.

3.4. Experimental determination of CO_2 capture efficiency and mass transfer

In the case study evaluated here, a sump with a diameter of 2.0 m and a depth of 2.0 m was equipped with eight low-pressure diffusers, enabling uniform air dispersion. Various airflow rates were tested, and the CO_2 concentrations at the inlet and outlet of the gas phase were continuously monitored to assess the capture efficiency. Results demonstrated that the CO_2 concentration in the air exiting the sump dropped consistently to near-zero values, with outlet concentrations in the range of 20–30 ppm, irrespective of the inlet airflow rate (Fig. 5). These values indicate that nearly all the CO_2 entering the system was transferred to the liquid phase, under the operational conditions tested (pH = 10, TIC = 100 mg/L). CO_2 removal efficiencies of up to 95% were observed, confirming the sump's capability as a highly effective passive DAC unit integrated within the production system. However, the total amount of CO_2 transferred remains directly dependent on the volume of air processed, with values ranging from 7 to 25 g/h. While increasing the air flow rate would theoretically allow for greater absolute CO_2 capture, in this specific setup, physical limitations of the existing facility prevented higher flow rates from being implemented. Despite this constraint, the findings validate that raceway reactor sumps can serve dual purposes—both as traditional CO_2 delivery points and as passive atmospheric CO_2 absorbers, offering a cost-effective and infrastructure-efficient solution for supplementing inorganic carbon in open algal production systems.

To better understand the mechanisms underlying direct air capture (DAC) of CO_2 in raceway reactors, a detailed analysis of the daily variation of culture conditions was conducted under real operating conditions. The system was operated in continuous mode, using ambient air as the sole source of CO_2, which was introduced via air bubbling in the sump. Throughout the day, different airflow rates from zero to 500 L/min were applied at specific intervals, as previously described [25], to

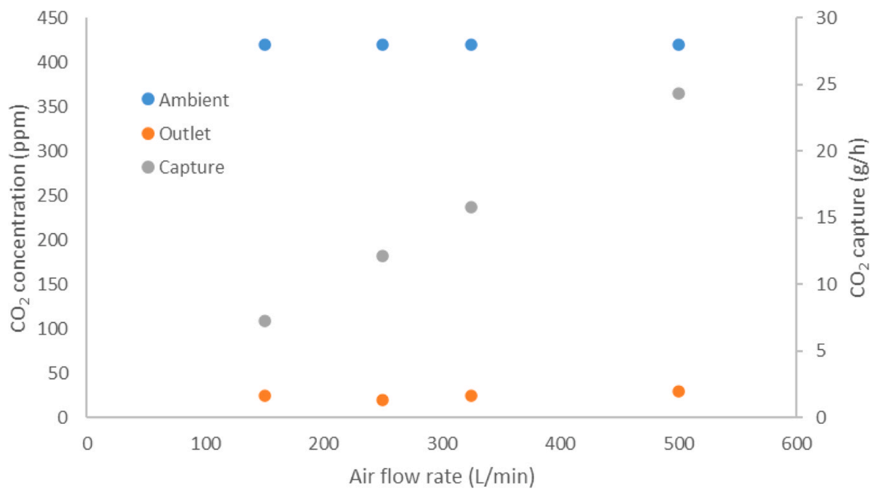

Fig. 5. Experimentally determined CO_2 capture efficiency and capture capacity in the sump of the 600 m^2 raceway reactor as a function of air flow rate under alkaline conditions (average bulk pH = 10, TIC = 100 mg L^{-1}).

experimentally determine the mass transfer capacity and photosynthesis rate. Results indicate that both culture temperature and dissolved oxygen concentration followed a diurnal pattern, closely aligned with the solar radiation profile (Fig. 6A). The temperature remains in the range of 22–35ºC, which was reported to be adequate for *Scenedesmus* sp. The operating temperature range of 22–35 °C corresponds to the typical outdoor conditions at the experimental site and to the optimal or near-optimal growth window of *Scenedesmus* spp.; at lower temperatures photosynthetic and metabolic rates decrease, while sustained temperatures above ~35–38 °C may induce thermal stress and reduced culture stability, although alternative microalgal species adapted to colder or hotter climates could be selected for site-specific operation. The system exhibited peak dissolved oxygen concentrations up to 17 mg O_2/L, which is consistent with typical values in raceway reactors supporting active biomass growth. This suggests that photosynthetic activity remained robust under the tested conditions.

When examining the CO_2 composition at the inlet and outlet of the sump, a modest fluctuation was observed in the inlet CO_2 concentration, primarily due to natural variations in atmospheric conditions (Fig. 6B). In contrast, the CO_2 concentration in the outlet gas stream consistently remained near zero throughout the day. This outlet profile followed a sinusoidal pattern, characterized by non-detectable values during daylight hours and slightly elevated concentrations during nighttime, reflecting the reduced photosynthetic CO_2 uptake and the onset of respiratory CO_2 release. The pH of the culture showed a pronounced diel variation. During the night, pH declined due to CO_2 accumulation from cellular respiration. In contrast, during the daylight period, the pH increased significantly as a result of CO_2 consumption through photosynthesis. The pH oscillated within a range of 9.7–10.2, a variation that reflects the dynamic balance between CO_2 capture and biological utilization. These observations confirm that the rate of CO_2 supplied via air bubbling in the sump was insufficient to fully satisfy the culture's CO_2 demand, especially during periods of high photosynthetic activity. Nevertheless, the pH remained within an acceptable operational window, suggesting that partial atmospheric CO_2 capture and carbon recycling within the reactor were sufficient to sustain biomass growth. Notably, the system maintained stable performance in continuous mode, with a dilution rate of 0.2 day^{-1} and biomass concentrations ranging from 0.4 to 0.6 g/L throughout the experiment. These results provide strong evidence that raceway reactors equipped with air-driven DAC through sump bubbling can support continuous microalgal production even under CO_2-limited conditions, although careful adjustment of airflow and operational parameters is required to ensure carbon balance and pH stability.

By processing the experimental data collected during the continuous operation of the raceway reactor, it is possible to quantify both the CO_2 capture capacity as mass of CO_2 captured per unit time and the CO_2 removal efficiency. Results demonstrate that the CO_2 capture capacity is dependent on the airflow rate provided to the sump, with observed values ranging from 5 to 25 g CO_2/h (Fig. 6C). These values are fully consistent with those obtained in previous short-term experiments, confirming the repeatability and robustness of the capture mechanism under continuous operation. Importantly, the CO_2 capture rate remained stable throughout the day, indicating that it is governed primarily by mass transfer dynamics rather than temporal changes in biological activity or solar radiation. While pH is known to influence the driving force for CO_2 transfer—as discussed previously—the pH values during the experiment remained relatively stable, averaging close to pH 10. This narrow range limits the variability in driving force, helping to isolate the impact of airflow rate on capture capacity. Slight variations were observed in CO_2 removal efficiency, which was calculated as the percentage of CO_2 transferred from the air into the liquid phase. During the daylight period, when photosynthetic activity and pH are at their peak, CO_2 removal efficiency approached 100%, reflecting optimal absorption conditions (Fig. 6C). During the night period, when biological CO_2 uptake ceases and respiratory CO_2 is released, the removal efficiency declined slightly, averaging around 90%. This minor reduction is attributed to the additional endogenous CO_2 produced by respiration, which accumulates in the culture broth and slightly diminishes the driving force for further CO_2 absorption.

3.5. *Comparison between theoretical predictions and experimental observations*

Experimental data allow for the analysis of the main phenomena occurring within the reactor and the separate quantification of the CO_2 mass balance in the system. Results confirm that during the night, respiration generates approximately 300 g CO_2 h^{-1} , which accumulates in the reactor because, due to the high pH, it is not stripped to the atmosphere (Fig. 7A). Additionally, during the night there is a net CO_2 uptake from the atmosphere of 54 g h^{-1} through the channel and 52 g h^{-1} through the paddlewheel, while CO_2 capture in the sump ranges from 5 to 14 g h^{-1} . During the daylight period, photosynthetic activity reverses the CO_2 flux—from production to consumption—reaching values as low as −1800 g h^{-1} . This demand is partially compensated by the increased CO_2 supply through the sump, where higher airflow rates (up to 30 g h^{-1}) were applied, and by additional atmospheric absorption through the channel and paddlewheel, accounting for 43 and 39 g h^{-1} ,

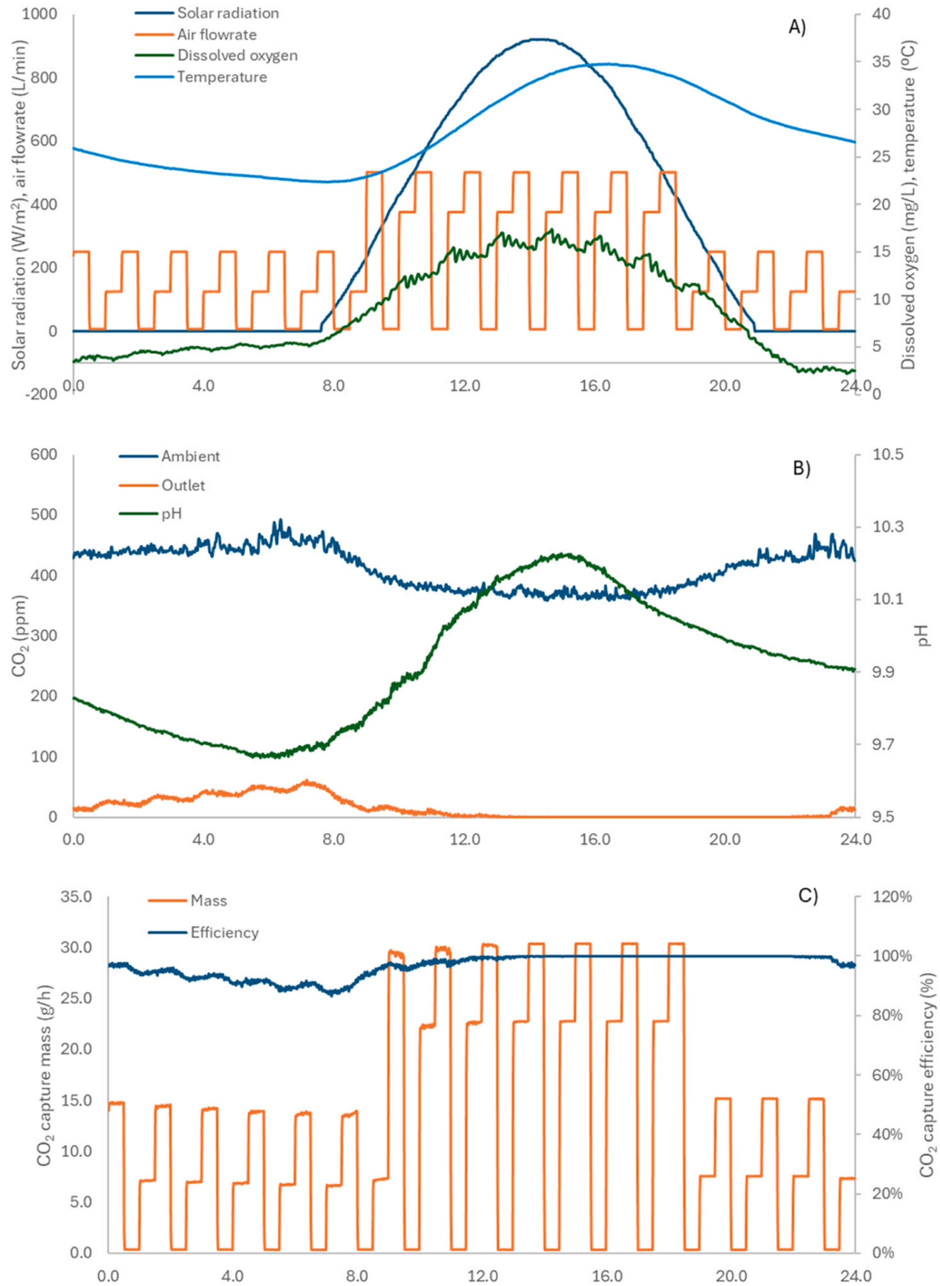

Fig. 6. Daily variation of operating conditions and CO_2 capture performance in the 600 m^2 raceway reactor operated under DAC conditions: (A) culture temperature, dissolved oxygen, and solar radiation; (B) inlet and outlet CO_2 concentrations in the sump together with the corresponding pH evolution; and (C) CO_2 capture rate and removal efficiency as a function of the air flow rate supplied to the sump.

respectively. Moreover, the supply of fresh culture medium containing dissolved inorganic carbon contributes up to 824 g h^{-1} of CO_2.

These results clearly demonstrate that the peak CO_2 demand during the central daylight hours is mainly satisfied by the inorganic carbon supplied with the incoming medium, while the other two major CO_2 sources are atmospheric absorption across the channel and paddlewheel sections. CO_2 absorption in the sump is comparatively less significant because aeration was not continuously applied; however, it remains the only contribution that can be enhanced in raceway ponds by increasing the aeration rate or enlarging the sump volume. If kept constant at 500 L/min, the air flow rate can provide up to 0.73 kgCO_2/day, and thus proportionally increases at higher air flow rates. The analysis of the overall CO_2 accumulation within the system indicates that the buffering capacity of the culture medium plays a central role in regulating CO_2 availability for microalgal cells (Fig. 7B). During the night, CO_2 accumulates in the culture medium, whereas during the daylight period it is consumed through photosynthesis. Consequently, atmospheric CO_2 capture occurs continuously over 24 h, while its biological fixation through photosynthesis takes place exclusively during daylight.

To demonstrate the feasibility of the proposed technology that couples microalgae production with Direct Air Capture (DAC) of atmospheric CO_2, experimental results over a period of four consecutive days with similar solar radiation conditions are presented (Fig. 8). The data validate the operational dynamics of the system, particularly in terms of CO_2 uptake from the atmosphere and CO_2 removal via sump outlet, while maintaining stable pH levels. Furthermore, dissolved oxygen concentrations displayed a consistent diurnal pattern, increasing from approximately 3 mg/L during the night to 30 mg/L during daylight hours, despite continuous aeration used both to supply CO_2 and to regulate oxygen levels. During this experimental period, the biomass

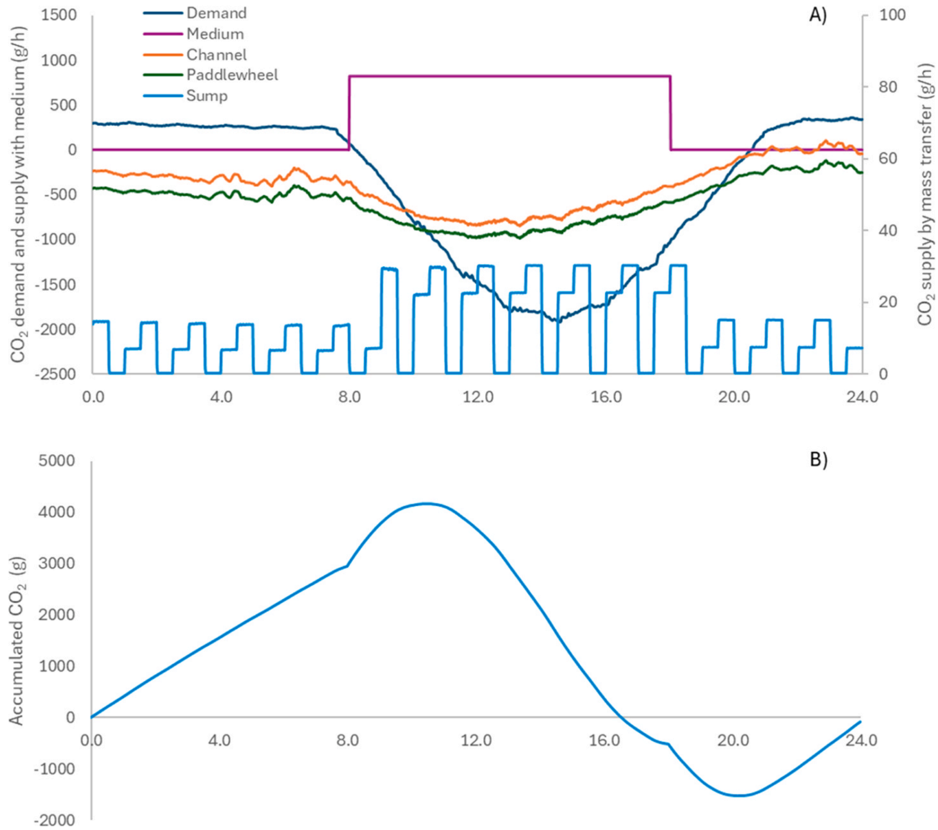

Fig. 7. Hourly CO_2 mass balance in the 600 m^2 raceway reactor illustrating the main fluxes and accumulation dynamics: (A) CO_2 demand and supply through the culture medium, channel, paddlewheel, and sump during daylight and night periods; and (B) overall carbon balance in the culture showing CO_2 accumulation and consumption patterns as a function of time.

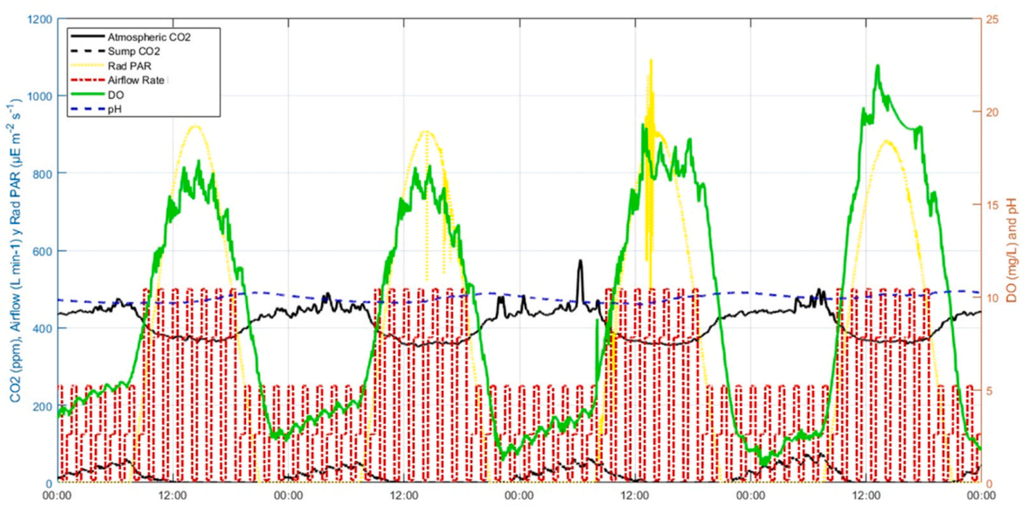

Fig. 8. Temporal evolution of key culture parameters during four consecutive days of continuous operation of the 600 m^2 raceway reactor under DAC conditions, illustrating the stability of the system over extended operation.

productivity was maintained at an average of 12 g/m^2·day. While not exceptionally high, this value is notable given the stress conditions imposed on the culture, particularly high pH and severe carbon limitation. Analytical measurements of Total Inorganic Carbon (TIC) in the culture broth revealed extremely low concentrations—approximately 20 mg/L—confirming that the system operated under conditions of extreme carbon limitation. Nevertheless, the observed productivity was comparable to that of other open raceway systems that use pure CO_2 supplementation, indicating the robustness and resilience of the microalgae under these challenging conditions. These findings provide strong evidence for the technical viability of the integrated microalgae-DAC system, particularly for deployment in remote or resource-limited settings. The ability to maintain biological productivity under ambient air conditions with minimal carbon availability supports its potential role in mitigating global warming and reducing atmospheric CO_2 concentrations through net-negative emissions. This innovative process has been formally recognized and is protected under patent by the company CHLYDRO (No WO2024245917).

The cost of Direct Air Capture (DAC) technologies remains a subject of intense debate, with reported estimates ranging from $30 to over $1000 per ton of CO_2 captured. In contrast, capture costs from flue gases are generally more constrained, typically falling within the $30–$100 per ton CO_2 range. A technical assessment by the American Physical Society (APS) in 2011 estimated the net cost of CO_2 capture from air at around $600 per ton, based on a benchmark system using aqueous sodium hydroxide as the absorbent. Subsequent optimization studies significantly reduced these cost projections to $518–$568 per ton with improved packing materials and process configurations, and as low as $309 per ton when integrating efficient heat recovery, low-cost natural gas, and plastic-based packing elements. The proposed microalgae-based DAC technology, using raceway reactors with sump-based air injection, introduces a novel approach where ambient air is bubbled through the sump to facilitate CO_2 absorption. To overcome the 0.3 bar pressure drop associated with this air delivery, the theoretical energy requirement is estimated at 2.86 kWh per kg of CO_2 captured. Assuming an electricity cost of €0.10 per kWh, this corresponds to an energy-related cost of €285 per ton of CO_2, which is comparable to the lower range of current DAC systems. Naturally, a more detailed economic assessment is required to validate the viability of this approach. However, it is important to note that this system can utilize renewable energy sources, making it particularly promising for remote or off-grid locations.

These findings represent an important first step in the development of robust and scalable microalgae-based systems for atmospheric CO_2 capture. Future work should focus on optimizing operational parameters such as pH and alkalinity to maximize CO_2 uptake, and on refining the carbon balance across the entire reactor, including analyses of biomass composition, dominant algal strains, and adaptive physiological responses. Ultimately, a new generation of reactor designs will be required to accommodate higher airflow rates while maintaining high CO_2 capture efficiency and minimizing energy input, which are key to the long-term sustainability and competitiveness of algal DAC technologies. The incorporation of digital twins and intelligent control methods can further enhance DAC–microalgae integration by enabling adaptive optimization of airflow, light, and pH dynamics [38]. The microalgal biomass produced under DAC conditions is suitable for existing markets such as biofertilizers and biostimulants, animal and aquaculture feed ingredients, and as a feedstock for bioenergy or biorefinery processes, where the additional value associated with atmospheric CO_2 capture can further enhance its economic and environmental relevance.

4. Conclusions

This study demonstrates the feasibility and transformative potential of integrating microalgae cultivation with Direct Air Capture (DAC) of atmospheric CO_2 in large-scale raceway pond reactors equipped with sump-based aeration. The system achieved up to 95% CO_2 removal efficiency while maintaining continuous biomass production exclusively from ambient air, confirming the capability of Scenedesmus sp. to sustain growth under extreme carbon limitation and alkaline conditions. Despite operating at moderate productivity (12 g m^{-2} day^{-1}), these results establish the technical proof of concept for bio-DAC as a dual-function process that simultaneously removes CO_2 from air and generates valuable biomass. The estimated energy demand for air bubbling ($\approx$ 2.9 kWh kg^{-1} CO_2) is comparable to or below that of current engineered DAC systems, highlighting the competitive advantage of this biologically integrated approach in terms of simplicity, cost, and compatibility with renewable energy sources. The integration of natural CO_2 fixation with passive gas–liquid mass transfer mechanisms opens a new pathway toward decentralized and carbon-negative biotechnologies. Future developments should target optimization of sump hydrodynamics, airflow distribution, and pH buffering, coupled with renewable-powered operation and biomass valorization strategies. These advances will enable scalable deployment of bio-DAC systems as a sustainable, low-energy alternative for atmospheric CO_2 mitigation and circular bio-resource production.

Authors contribution

R. Arraga designed and conducted the experiments, performed data collection and analysis of CO_2 mass transfer and carbon balance, and led the manuscript writing and figure preparation.

M. Barceló-Villalobos contributed to the experimental setup and reactor operation, assisted with data interpretation, and participated in manuscript drafting and critical revisions.

R. Esteitie supported the analytical methodology, performed calculations of energy demand and CO_2 capture efficiency, and contributed to data validation and discussion.

M. Ahaddouch assisted with mass transfer modeling, equilibrium calculations, and preparation of graphical results, and contributed to manuscript editing.

C. Sánchez-Salinas developed the data acquisition and control architecture, managed SCADA integration, and contributed to analysis of the monitoring data.

F. G. Acién conceptualized the study, coordinated the research activities, secured funding, supervised all stages of the work, and finalized the manuscript for submission.

All authors reviewed and approved the final manuscript.

CRediT authorship contribution statement

M. Ahaddouch: Methodology, Investigation, Formal analysis. **R Esteitie:** Writing – original draft, Software, Formal analysis. **F.G. Acién:** Writing – review & editing, Methodology, Conceptualization. **C. Sánchez-Salinas:** Validation, Supervision, Software. **R. Arraga:** Methodology, Investigation. **M. Barceló-Villalobos:** Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

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Data availability

Data will be made available on request.

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