

Design and Performance Evaluation of Flat-Panel Airlift Photobioreactors with Integrated Multi-Parameter Monitoring for Microalgae Cultivation

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Abstract

Microalgae productivity depends on pH, temperature, dissolved oxygen, CO₂, light, culture density and liquid level, which interact and shift within hours. This study designs flat-panel airlift photobioreactors at 2 L and 20 L and develops a low-cost, ESP32-based system that logs all seven parameters in real time, adding measured PAR and turbidity-based biomass estimation to an existing five-sensor platform. The system is evaluated for accuracy, precision, drift and fouling against reference instruments while cultivating *Nannochloropsis* sp. in modified Conway medium and *Scenedesmus quadricauda* in pretreated industrial effluent, and reactor performance is assessed by specific growth rate, doubling time, volumetric productivity and nutrient removal. Preliminary calibration shows errors of 2.6–7.8% for temperature, pH and dissolved oxygen against a 2% target, with PAR calibration awaiting a fixed light source. In flask acclimatization, *S. quadricauda* grew at 0.18–0.19 d⁻¹ in its exponential phase and reached 1.34 g/L. Baseline analysis of the plant effluent found it within Class C effluent limits but with nitrogen and phosphorus at about 1% of BG11 levels. A Python analysis pipeline is prepared to compute growth descriptors from the logged data and to model how temperature, pH and light jointly affect growth.

Keywords: microalgae; flat-panel airlift photobioreactor; IoT sensor monitoring; *Nannochloropsis*; *Scenedesmus quadricauda*; wastewater treatment

1. Background

Microalgae are cultivated for a broad range of high-value and environmental applications: biofuel feedstock, omega-3 fatty acids (EPA/DHA), aquaculture feed, biological carbon capture, and, increasingly, the biological treatment of nutrient-rich wastewater [1]. Across all of these applications, productivity depends on a set of interacting culture parameters that must be held within organism-specific ranges: pH, temperature, dissolved oxygen (DO), carbon dioxide (CO₂), light (photosynthetically active radiation, PAR), culture density (turbidity), and liquid level. These parameters shift on timescales of minutes to hours and interact strongly; photosynthetic CO₂ uptake, for instance, drives coupled pH and DO oscillations over a light–dark cycle. Reliable cultivation therefore depends on the ability to observe them continuously and in real time.

The central problem this study addresses is the development of an instrument capable of doing this reliably, an integrated, real-time, multi-parameter sensor system, and the verification of its accuracy upon scale-up. Most reported low-cost monitoring systems are validated in a single culture matrix. Real deployments are less forgiving: a defined marine medium and a turbid, variable industrial wastewater place very different demands on the same sensors, particularly the optical ones.

Scope and limitations. The study evaluates sensor accuracy, fouling, and biomass calibration using two microalgae species, *Nannochloropsis* sp. (saline) and *Scenedesmus quadricauda* (freshwater), in 2 L and 20 L flat-panel reactors, monitoring seven operating conditions: temperature, pH, turbidity, CO₂ concentration (ambient air), PAR, water level and dissolved oxygen. Because these findings depend heavily on these exact species, culture media, and reactor setups, they cannot be generalized to other systems without further validation.

The objectives of the study are set out in Section 1.1, and Sections 1.2–1.6 review the related literature in five areas: what each organism needs to grow, how those needs are monitored, how flat-panel airlift reactors are designed and scaled, how microalgae treat wastewater, and how sensor accuracy is judged.

1.1 Research Objectives

General objective

To design and evaluate the performance of an integrated real-time multi-parameter sensor monitoring system that measures pH, temperature, water level, dissolved oxygen, influent and effluent CO₂ concentration, PAR, and turbidity in flat-panel airlift photobioreactors of *Nannochloropsis* and *Scenedesmus* cultures.

Specific objectives:

1. Design flat-panel airlift photobioreactors of acrylic, indicating design considerations such as light path length, height-to-length ratio (H/L), surface-area-to-volume ratio (SA/V), and the downcomer-to-riser area ratio (Ad/Ar).
2. Cultivate *Nannochloropsis* sp. in modified Conway medium, and *Scenedesmus quadricauda* in pretreated industrial wastewater.
3. Develop a real-time multi-parameter sensor monitoring system that measures pH, temperature, water level, dissolved oxygen, influent and effluent CO₂ concentration, PAR, and turbidity by integrating these sensors in an ESP32 microcontroller and displaying measurements in a dashboard for monitoring.
4. Evaluate the accuracy and precision of the integrated multi-parameter sensor monitoring system by calculating the percent error and standard deviation across selected timeframes.
5. Evaluate the performance of the flat-panel airlift photobioreactors by calculating their volumetric biomass productivities, specific growth rates, and doubling times, and compare their performance with existing PBR systems. For the wastewater treatment, determine the initial and final concentrations of wastewater characteristics and compare them to obtain the percent removal of each contaminant.

1.2 Microalgae Growth Requirements and Parameter Effects

Both organisms in this study respond to the same interacting variables, but their tolerances differ, and for *Nannochloropsis* they also differ from strain to strain. *Nannochloropsis* is a marine microalga valued for fast growth and high lipid content, which can reach 70% of dry weight with over 35% of those lipids as polyunsaturated fatty acids [2]. Reported biomass productivities reach up to $3.2 \text{ g L}^{-1} \text{ d}^{-1}$, and Ihadjadene et al. [2] attribute the wide spread in published values mainly to how well process conditions were held, rather than to the organism's capacity.

Temperature. The optimum temperature for *Nannochloropsis* is commonly reported as 24–26 °C [3]. Ihadjadene et al. [2] estimated cardinal temperatures of 6.3, 24.5 and 30.0 °C for strain CCAP 211/78, a narrow margin between the optimum and the lethal maximum that calls for close temperature control. Tamburic et al. [3] found that a 15–25 °C daily temperature cycle produced the same chlorophyll-based growth as a constant 20 °C, but caused more damage to photosystem II when high temperature coincided with strong midday light. Tolerance is strain-dependent: *Nannochloropsis* sp. MASCC 11 grew best at 35 °C and still grew at 40 °C [4].

pH and CO₂. In culture media, CO₂, bicarbonate and pH are chemically coupled: injected CO₂ lowers the pH, and photosynthetic uptake of inorganic carbon raises it again [5]. Reported optima vary with strain and mode of growth. Ihadjadene et al. [2] estimated an optimal pH of 7.8 for CCAP 211/78, with growth limits at pH 4.1 and 11.3. Razzak et al. [5] obtained the highest mixotrophic growth of *N. oculata* with 8% CO₂ in the aeration gas, with pH 5.5–6.5 favorable, while *Nannochloropsis* sp. MASCC 11 gave its highest biomass at pH 9.0 and 5% CO₂, even though other strains have been inhibited at 5–10% CO₂ [4]. Optimal conditions also depend on the product: in a factorial study of *N. oculata*, growth was highest at pH 9.5, 20 °C and

continuous light, while protein, fatty acid and EPA contents peaked under different conditions [6].

Light. Light and carbon supply must be matched. For *N. oceanica* CCMP1779, the CO₂ concentration giving the highest biomass rose from 6% at 20 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (1.24 g/L) to 50% at 80 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (2.45 g/L), while at 120 $\mu\text{mol m}^{-2} \text{s}^{-1}$ the highest yield fell to 0.97 g/L, past a photoinhibition threshold between 80 and 120 $\mu\text{mol m}^{-2} \text{s}^{-1}$ [7]. Ihadjadene et al. [2] estimated an optimal light intensity of 112.7 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for CCAP 211/78, and showed that predicting growth at high cell density requires modelling how light is absorbed and scattered inside the reactor.

Dissolved oxygen. Photosynthetic oxygen accumulates in closed reactors and inhibits growth. In *Nannochloropsis* sp., the specific growth rate was about 0.48 d⁻¹ between 20% and 75% of air saturation, then fell linearly to 0.18 d⁻¹ at 250% [8]. This is why closed systems remove oxygen actively, for example through automated bleed valves [2].

Scenedesmus quadricauda, the second organism, is a freshwater species that grows in wastewater and removes nutrients from it [9]; its use in treatment is reviewed in Section 1.5. Taken together, these studies show that CO₂ interacts with pH, light with CO₂, and temperature with light, which is why this study measures the parameters together and continuously rather than one at a time.

1.3 Real-Time Sensor Technologies and IoT Monitoring for Algal Culture

Scaling microalgae production requires standardized, measurable indicators of culture condition, because the stresses of large-scale growth, such as swings in temperature, light or pH, are what

threaten culture viability and product quality [10]. Low-cost microcontroller platforms have made continuous monitoring of the basic physical channels practical. Tham et al. [11] built an IoT photobioreactor that logged liquid level, temperature and pH through an Arduino NodeMCU board to a smartphone app; its readings matched manual measurements closely, except for liquid level. Jamiaan et al. [12] streamed electrical conductivity, oxidation–reduction potential, pH and temperature over LoRaWAN to a cloud database and dashboard, and reported less reliance on manual measurement.

Biomass is the hardest variable to measure online. Benavides et al. [13] built an RGB light-transmission sensor for about US\$70 that tracked microalgae concentration with $R^2 = 0.998$ during exponential growth, behaving similarly to a commercial near-infrared probe over a 163-hour batch. Optical estimates carry a known weakness: the relationship between optical density and dry weight shifts as cells change their pigment content. Griffiths et al. [14] showed that a calibration made under one pigment condition gave average errors of about 52% at 680 nm but about 25% at 750 nm, which is why 750 nm is preferred and why calibration curves must match the culture's growth stage and condition. In turbid, colored media such as industrial wastewater, the medium itself scatters and absorbs light, so optical channels also need blank correction against cell-free medium.

Sensor fouling adds a time limit to every calibration. In marine in-situ monitoring, biofouling can degrade data quality within about a week of deployment [15]. A calibration therefore cannot be assumed to hold for a whole cultivation run, so drift and fouling have to be tracked over time.

The systems reviewed here each cover part of the problem: physical channels without biomass [11], [12], or biomass alone [13]. None of them combines pH, temperature, DO, CO₂, level, PAR

and turbidity in one calibrated system, or validates the same sensors in both a defined medium and a real wastewater, which is the gap this study addresses.

1.4 Flat-Panel Photobioreactor Design, Operation, and Scale-up

Flat-panel reactors keep most of the culture close to the lit surface by using a short light path.

Light still falls off steeply with depth as biomass rises: Ihadjadene et al. [2] found that a two-flux model, which accounts for both absorption and scattering by cells, predicted light distribution in a 0.02 m flat panel better than the Beer–Lambert approach over a wide range of biomass concentrations. Self-shading also changes during a run. Tamburic et al. [3] linked the rise in midday photosystem II yield over their culture period to increased self-shading as cell density grew, and noted that mixing, which moves cells between lit and shaded zones, matters more as cultures thicken. The 2 L reactor in this study has a 5 cm light path, two and a half times that of the 0.02 m panels studied by Ihadjadene et al. [2], so light attenuation at high density and the measurement of PAR carry more weight here.

Airlift circulation provides this mixing without impellers: gas injected into the riser drives the liquid upward, and it returns through the downcomer. This is why the downcomer-to-riser area ratio (A_d/A_r) is a design parameter alongside light path, H/L and SA/V . Flat-plate reactors have been characterized specifically for microalgae production [16], and closed flat panels are now operated at pilot scale for *Nannochloropsis* [2].

Two scale-up routes appear in the literature. The ProviAPT pilot system scales out: it is an array of parallel panels identical to the laboratory unit, so the light path and geometry do not change [2]. Its pilot campaign reached $0.7 \text{ g L}^{-1} \text{ d}^{-1}$ under temperatures that swung between 8.5 and 21.5 °C, against $4.94 \text{ g L}^{-1} \text{ d}^{-1}$ predicted under fully controlled optimal conditions and 1.2 and 3.2 g

$\text{L}^{-1} \text{d}^{-1}$ in earlier outdoor summer campaigns (de Vree et al. and Norsker et al., as reported in [2]). This study scales up instead, enlarging a single panel from 2 L to 20 L while keeping its light path and height-to-length ratio (Section 2.1). Matching these ratios does not by itself guarantee the same mixing, mass transfer or light climate, which is why identical instrumentation is deployed at both scales: to check whether conditions, and the sensors' readings of them, carry over.

1.5 Microalgae-Based Wastewater Treatment

Nutrient-rich wastewater discharged into waterways can drive harmful algal overgrowth, but under controlled conditions microalgae can remove those nutrients and metals while producing usable biomass [1]. Using wastewater as the growth medium also reduces the freshwater and fertilizer needed for cultivation [5].

Scenedesmus quadricauda has been tested directly for this purpose. In primary settled wastewater, it removed over 90% of orthophosphate in acclimated cultures and over 95% of ammonia nitrogen in unacclimated cultures within five days; in 25% and 50% dilutions of filtrate wastewater, it removed over 80% of phosphate within six days and over 90% of ammonia nitrogen within five days [9]. Nutrient removal can also be combined with CO_2 capture: *N. oculata* grown in synthetic wastewater under 8% CO_2 removed 98.9% of ammonia and 88.2% of nitrate but only 18.9% of phosphate over 18 days, taking up ammonium in preference to nitrate [5].

Industrial effluent poses different problems from municipal wastewater. The Cornersteel effluent used in this study was characterized in June 2026 [17] (Section 3.3): it meets DAO Class C water standards by a wide margin, but it is severely depleted in nitrogen and phosphorus, at roughly

1% of BG11 concentrations, with an N:P mass ratio near 30:1. Phosphorus is therefore a likely limiting nutrient, which is why nutrient balancing is part of the pretreatment (Section 2.2). Suspended solids and color in the effluent also interfere with the turbidity sensor, so the effluent is settled and filtered before use, and optical readings are blank-corrected against cell-free effluent (Section 2.3).

1.6 Calibration, Agreement, and Statistical Methods for Sensor Validation

A sensor is validated by comparing it with a reference instrument, and the comparison has to measure agreement, not just association. Bland and Altman [18] showed that a correlation coefficient is a misleading measure of agreement between two measurement methods: two instruments can correlate almost perfectly while one reads consistently high. They proposed instead to examine the differences between paired readings, plotted against their means, with limits of agreement set at the mean difference ± 1.96 standard deviations. This study reports percent error and standard deviation against reference instruments (Objective 4) and adds Bland–Altman analysis where enough paired readings exist.

For biomass, the turbidity sensor is calibrated by regression against optical density at 750 nm and gravimetric dry weight, reported with R^2 as in comparable low-cost optical sensors [13]. Because pigment changes and fouling shift these relationships over time [14], [15], calibration is repeated across growth stages and checked for drift during each run.

Growth is summarized by the specific growth rate, $\mu = \ln(X_{\square}/X_0)/(t_{\square} - t_0)$, the doubling time, $\ln 2/\mu$, and the volumetric productivity, $\Delta X/\Delta t$ [5]. Because μ describes exponential growth, it is computed over the exponential phase identified from the growth curve rather than across the lag

and stationary phases; a fit across the whole run averages in the slowdown and understates the rate (Section 3.2).

2. Methods

2.1 Design and Scale-up of Flat-Panel Airlift Photobioreactors

Flat-panel airlift photobioreactors are designed based on the following geometric design parameters: height-to-length ratio (H/L), light path length, downcomer-to-riser area ratio (A_d/A_r), and surface-area-to-volume ratio (SA/V). Triplicate runs using 2 L photobioreactors will be cultured at a light path length of 5 cm, keeping all other parameters constant. The design is then scaled up from 2 L to 20 L; Table 1 compares the two reactors.

The 2 L flat-panel airlift photobioreactor was fabricated from 6 mm thick cast acrylic and configured as a vertically oriented rectangular reactor. The overall reactor dimensions were 210 mm in length, 270 mm in height, and 50 mm in width. Gas-driven circulation was established through a concentric rectangular-prism riser positioned within the reactor chamber. The riser had a length of 150 mm, a width of 38 mm, and a height of 114 mm, and was elevated 19 mm above the reactor base. The geometric configuration of the reactor resulted in a surface-area-to-volume ratio (SA/V) of 56.93 m^{-1} and a height-to-length ratio (H/L) of 1.29. The downcomer-to-riser area ratio (A_d/A_r) of the PBR is approximately 1.56.

The 20 L reactor is also built from acrylic (PMMA). It measures 630 mm in length, 820 mm in height and 50 mm in thickness and holds a liquid height of 634 mm. Circulation runs through two square draft tubes with an equivalent diameter of 50 mm, sandwiched between the two panels and equally spaced from the sides. Each tube is 381 mm tall, 60% of the liquid height, and starts 80 mm above the base. The base is rounded and the panels have no seams. The scale-up

keeps the 50 mm light path and an H/L of about 1.3, so cells at both scales are the same distance from the lit surface. The two draft tubes, however, take up only about 16% of the panel's cross-section, which raises Ad/Ar from about 1.56 to about 5.3; because Ad/Ar governs airlift circulation (Section 1.4), mixing at 20 L may differ from mixing at 2 L.

Table 1. *Geometry of the 2 L and 20 L flat-panel airlift photobioreactors*

Parameter	2 L reactor	20 L reactor
Material	Cast acrylic, 6 mm thick	Acrylic (PMMA)
Length × height × thickness (mm)	210 × 270 × 50	630 × 820 × 50
Light path (mm)	50	50
Liquid height (mm)	—	634
Riser	One rectangular prism, 150 × 38 × 114 mm, 19 mm above the base	Two square draft tubes, 50 × 50 mm, 381 mm tall, 80 mm above the base
Height-to-length ratio, H/L	1.29	1.30
Surface-area-to-volume ratio, SA/V (m ⁻¹)	56.93	45.6 ^a
Downcomer-to-riser area ratio, Ad/Ar	1.56	5.3 ^a
Base	—	Rounded, no seams

Note. 2 L values are from the fabricated reactor and 20 L values from the design specification. ^a Calculated by the author from the specified dimensions, to be confirmed: SA/V on the same basis as the 2 L value (total surface area of the panel over its enclosed volume), and Ad/Ar as the panel cross-section outside the draft tubes divided by the draft-tube cross-section, ignoring wall thickness.

2.2 Cultivation Protocol

Two cultivation systems are run. *Nannochloropsis* sp. is cultivated in modified Conway medium made up in seawater (Table 2). Each run is inoculated at 20% (v/v) and grown under 10,000 lux on a photoperiod of 8 h light and 16 h dark, with aeration at 0.2 vvm and no CO₂

supplementation, at ambient room temperature. A run lasts about 15 days and is harvested when growth reaches stationary phase. Culture medium is mass-produced in a 20 L mixing tank made of SS316 stainless steel. [To be added: salinity of the medium.]

Table 2. *Composition of modified Conway medium*

Stock solution	Component	Stock concentration	Final concentration in medium
Main nutrient stock	KNO ₃	117.0 g/L	117 mg/L
	Na ₂ EDTA	45.0 g/L	45 mg/L
	H ₃ BO ₃	33.6 g/L	33.6 mg/L
	Na ₂ HPO ₄ ·H ₂ O	20.0 g/L	20 mg/L
	FeCl ₃ ·6H ₂ O	1.3 g/L	1.3 mg/L
	MnCl ₂ ·4H ₂ O	3.6 g/L	3.6 mg/L
Trace-metal stock	ZnCl ₂	2.1 g/100 mL	21 µg/L
	CoCl ₂ ·6H ₂ O	2.0 g/100 mL	20 µg/L
	(NH ₄) ₆ Mo ₇ O ₂₄ ·4H ₂ O	0.9 g/100 mL	9 µg/L
	CuSO ₄ ·5H ₂ O	2.0 g/100 mL	20 µg/L
Vitamin stock	Thiamine (vitamin B ₁)	200 mg/200 mL	1 mg/L
	Cyanocobalamin (vitamin B ₁₂)	100 mg/200 mL	0.5 mg/L

Note. Stock solutions are made in distilled water. One milliliter of trace-metal stock is added per liter of main nutrient stock, 1 mL of main nutrient stock per liter of seawater, and 1 mL of vitamin stock per liter of medium; final concentrations are calculated from these volumes.

Scenedesmus quadricauda is cultivated in pretreated effluent from the wastewater treatment plant of Cornersteel Systems Corporation. The effluent is first characterized and pretreated (settling, filtration, neutralization and nutrient balancing) before use, and the optical sensors are managed and logged over the run. It is analysed before and after cultivation for chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrate, phosphate, sulfate, carbonates and

heavy metals, from which percent removal is calculated (Section 2.5). The in-house laboratory cannot yet run these analyses, so samples go to a third-party laboratory, Ostrea Mineral Laboratories, which follows Standard Methods for the Examination of Water and Wastewater (24th ed.): COD by open reflux, BOD by the 5-day test, nitrate as $\text{NO}_3\text{-N}$ by the brucine colorimetric method (USEPA Method 352.1), phosphate by the stannous chloride method, sulfate turbidimetrically, and heavy metals by ICP-OES [17]. Ammonia, measured as $\text{NH}_3\text{-N}$ with an ion-selective electrode, is reported alongside and counts toward total nitrogen. [To be added: the method for carbonates, which were not part of the June 2026 analysis.]

Scenedesmus quadricauda was first cultured in BG11 medium to acclimatize it to its environment. The composition of BG11 medium is given in Table 3. Preparation of BG11 medium followed the procedure prescribed by Stanier et al. [19]. This acclimatization was carried out in 500 mL flasks: absorbance at 750 nm was read daily in triplicate and converted to dry biomass with a gravimetric standard curve (Section 3.2).

Table 3. *Composition of BG11 medium per liter of distilled water*

Component	Concentration (mg/L)
NaNO_3	1,500
$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	36
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	75
K_2HPO_4	40
Ferric ammonium citrate	6
Citric acid	6
Na_2EDTA	1
$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$	1.81
H_3BO_3	2.86

Component	Concentration (mg/L)
Na ₂ CO ₃	20
Na ₂ MoO ₄ ·2H ₂ O	0.39
ZnSO ₄ ·7H ₂ O	0.22
Co(NO ₃) ₂ ·6H ₂ O	0.0494
CuSO ₄ ·5H ₂ O	0.079

Cultures are sampled every 24 hours to build a growth curve, which serves as the basis for determining the growth stage of the microalgae. Cultures are harvested once the growth curve plateaus, indicating that they have reached stationary phase.

For both systems, manual reference measurements of the monitored parameters are taken to determine the accuracy and precision of the sensors in the PBR system. Because the photobioreactor uses a turbidity sensor to quantify microalgal concentration, a standard curve correlating turbidity and biomass concentration will be generated.

2.3 Instrumentation of the Flat-Panel Airlift Photobioreactor System

An integrated, ESP32-based sensor array logs the seven parameters synchronously on a common timebase, streaming live values over MQTT (HiveMQ), archiving to Firebase, presenting an operator dashboard (Netlify), and issuing critical-value alerts (EmailJS). This distinguishes the baseline for pH, DO, CO₂, temperature, and water level, read through an ADS1115 analog front end and digital inputs, together with relay-based actuator control and a 3:1 red–blue LED system, from the additions made in this study: a measured PAR input (a quantum/PAR sensor logged as data rather than only used as an LED set-point) and a turbidity sensor for real-time dry biomass estimation. This section provides a block diagram (sensors → ESP32 → cloud logging/streaming → dashboard and alerting), sensor specifications and placement, and enclosure considerations.

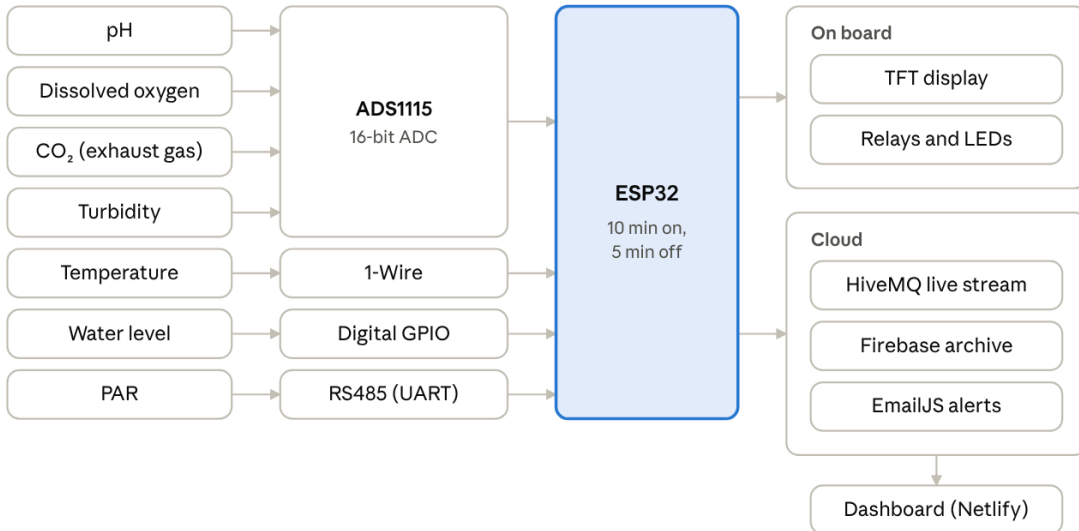
The same instrumentation is deployed identically on the 2 L and 20 L reactors so that measurements are directly comparable across scales.

The firmware runs a startup sequence followed by a repeating cycle of 10 minutes of active sensing and 5 minutes of cooldown. It also drives the relay-controlled actuators (active-LOW solid-state relays) and the LED PAR control, and shows readings on a local 2.8-inch TFT display. In bench testing, the breadboard prototype ran continuously for about three hours without faults, at a stable current draw of about 381 mA. The electronics are housed in a 3D-printed enclosure sized from the measured sensor dimensions, with openings for the relay module, BNC connectors, IP-rated cable glands and the TFT display [20]. Figure 1 shows the data path from the sensors to the operator, and Table 4 lists each sensor, its interface and its placement.

Figure 1. *Data path of the monitoring system*

Seven sensors report through one ESP32 to the display, cloud and alerts

Data path of the monitoring system; arrows show the direction of data



monitoring system · 7 sensors, 4 interfaces, 1 ESP32, on-board and cloud outputs

Table 4. *Sensors, interfaces and placement*

Parameter	Sensor	Interface to ESP32	Placement	Calibration status
pH	DFRobot SEN0161 analog pH kit	Analog, via ADS1115	In culture	Complete; verified
Temperature	DFRobot DS18B20 waterproof probe (KIT0021)	1-Wire (GPIO)	In culture	Complete; verified
Dissolved oxygen	DFRobot SEN0237-A	Analog, via ADS1115	In culture	Complete; partly verified
CO ₂	DFRobot SEN0219 infrared	Analog, via ADS1115	Dry sampling chamber on the exhaust air line, with water trap and filter	Complete; verified
Water level	DFRobot SEN0204 non-contact	Digital (GPIO)	Outside the reactor wall	Complete; verified
PAR	RS485 PAR sensor	RS485, via UART transceiver	Outside the reactor, on the plane of the lit wall, mid-height	Initial; partly verified
Turbidity	DFRobot analog turbidity sensor (SEN0189)	Analog, via ADS1115	In culture	Initial; partly verified

Note. Calibration status as of September 2026 [20]. [To be added: exact positions of the in-culture probes in the 2 L and 20 L reactors.]

Each sensor is calibrated against a reference instrument, and accuracy, precision, drift, and response time are reported as measured quantities. Because the turbidity–biomass relationship is organism- and matrix-specific, separate calibration curves are constructed for each organism against optical density (OD_{750}) and gravimetric dry weight; for the wastewater cultures these are blank-corrected against cell-free effluent of the same batch to separate algal turbidity from the intrinsic turbidity and color of the effluent. PAR readings are calibrated against a reference quantum sensor, and the spatial uniformity of incident light across the panel is mapped.

Calibration is performed in both matrices (saline Conway medium and industrial wastewater) so that matrix effects on each channel, particularly the pH reference junction in saline media and the optical channels in turbid media, are quantified.

2.4 Performance Evaluation of the Flat-Panel Airlift Photobioreactor

- **Descriptive analysis and variability.** Summary statistics for each parameter and characterization of baseline process variability, including the amplitude and timing of the diurnal pH and DO oscillations and the shape of the turbidity-tracked growth curve.
- **Sensor validation.** Accuracy, precision, drift, and response time against reference instruments; correlation and agreement analysis (e.g., Bland–Altman [18]) between logged and manual measurements; and regression models relating turbidity to OD and dry weight for each organism and matrix.
- **Cross-scale evaluation.** Comparison of sensor readings, and of the sensor-to-reference relationships, between the 2 L and 20 L reactors.
- **Growth characterization.** Derived growth descriptors (specific growth rate, doubling time, volumetric biomass productivity) computed from the validated turbidity/biomass data and related to the measured parameters were informative.

Statistical tests use a significance level of $\alpha = 0.05$. All analysis is scripted in Python (pandas, NumPy and SciPy) so that it can be reproduced and rerun as data accumulate (Section 2.6).

2.5 Calculations

Sensor accuracy is expressed as percent error against the reference instrument. Biomass concentration X (g/L) is obtained from absorbance at 750 nm through the gravimetric standard curve. The specific growth rate μ is the slope of $\ln X$ against time during the exponential phase, from which the doubling time t_d and the volumetric biomass productivity P_x follow [5].

```
\begin{aligned}
\text{Percent error} &= \frac{|\text{sensor} - \text{reference}|}{\text{reference}} \\
&\times 100 \\
\mu &= \frac{\ln X_2 - \ln X_1}{t_2 - t_1} \quad \text{exponential phase} \\
t_d &= \frac{\ln 2}{\mu} \\
P_X &= \frac{X_{\max} - X_0}{t_{\max} - t_0}
\end{aligned}
```

Removal of each wastewater constituent is calculated from its concentration before (C_0) and after (C_f) cultivation:

$$\text{Removal (\%)} = \frac{C_0 - C_f}{C_0} \times 100$$

2.6 Data Analysis and Growth Modelling

Two Python scripts carry out the analysis, so that every table and figure can be regenerated as new data arrive. The first computes the calibration statistics and growth descriptors in Section 3 directly from the calibration records and the absorbance workbook. The second analyses the logged sensor data from the dashboard export. It removes sensor-off and out-of-range readings (for example, pH stuck at 0 or 14), averages the readings into 15-minute steps that match the sensor duty cycle, converts turbidity to biomass with the turbidity standard curve, and computes the specific growth rate as the slope of $\ln X$ over a rolling 3-hour window during the light period. The second script then describes how the parameters relate to each other and to growth. Spearman correlations show which channels move together, such as DO rising while exhaust CO_2 falls during photosynthesis. Correlation misses a parameter whose best level lies in the middle of its range, so growth is also fitted to a multiplicative model of the kind validated for *Nannochloropsis* by Ihadjadene et al. [2]:

$$\mu = \mu_{\max} \cdot f(T) \cdot f(\text{pH}) \cdot f(I)$$

Here $f(T)$ is the cardinal temperature model with inflection [21], $f(\text{pH})$ is the cardinal pH model [22], and $f(I)$ is a light-response curve that rises to a peak and falls under photoinhibition. Each function equals 1 at that parameter's best level, so the fitted peaks give the best temperature, pH and light intensity, each reported with a 95% confidence interval and the range that keeps growth within 90% of its maximum. DO and CO_2 are changed by the culture itself, so they are not treated as set points; the script instead reports the range each held during the fastest-growing

quarter of the run, for use as alarm thresholds. On simulated runs with known best levels of 26 °C, pH 8.2 and 180 $\mu\text{mol m}^{-2} \text{s}^{-1}$, the model recovered 25.9 °C, pH 8.19 and 181 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The model can locate a best level only if the data cover both sides of it. Runs held at a single set point, such as the triplicate 2 L runs in Section 2.1, will give growth descriptors and sensor-validation data but not best levels; the script detects this and reports it instead of extrapolating. Under the current cultivation protocol (Section 2.2), light is fixed at 10,000 lux and temperature follows the room, so the light response cannot be estimated and the temperature estimate will cover only the range of room temperatures the runs happen to span. Estimating best levels requires additional runs at three or more set points of temperature, pH and light, spanning the expected optimum.

3. Results

No sensor channel tested so far meets the project's 2% accuracy target. In flask acclimatization runs, *Scenedesmus quadricauda* grew at 0.18–0.19 d^{-1} in its exponential phase and reached up to 1.34 g/L. Cultivation in the 2 L reactor begins in October 2026, after fabrication of the revised design. The baseline analysis of the plant effluent is given in Section 3.3.

3.1 Sensor Calibration

During sensor-suite development (August–September 2026), the DO, pH, temperature and PAR sensors were compared with reference instruments [20]. Table 5 summarizes the results, and Tables 6–8 give the readings.

Table 5. Sensor calibration against reference instruments

Parameter	Sensor	Reference instrument	Readings (n)	Mean absolute error	Mean percent error (%)	Within 2% target
Dissolved oxygen	DFRobot SEN0237-A	Reference DO meter	3	0.37 mg/L	7.84 ± 0.88	No
pH	DFRobot SEN0161	Reference multimeter	2	0.35 pH units	5.71	No
Temperature	DFRobot DS18B20 (KIT0021)	Reference multimeter	2	0.65 °C	2.56	No
PAR	RS485 PAR sensor	Reference PAR meter	4	12.3	35.65	No

Note. ± is the standard deviation, available for DO only because it is the only channel with repeat readings.

Table 6. Dissolved oxygen sensor against the reference DO meter (tap water, 22 °C)

Trial	DO sensor (mg/L)	DO meter (mg/L)	Absolute difference (mg/L)	Percent error (%)
1	5.03	4.65	0.38	8.17
2	5.00	4.68	0.32	6.84
3	5.10	4.70	0.40	8.51
Mean ± SD	5.04 ± 0.05	4.68 ± 0.03	0.37 ± 0.04	7.84 ± 0.88

Table 7. pH and temperature sensors against the reference multimeter

Buffer	pH sensor	pH reference	pH absolute error	pH error (%)	Temp. sensor (°C)	Temp. reference (°C)	Temp. absolute error (°C)	Temp. error (%)
pH 4.0	4.06	4.22	0.16	3.79	26.2	25.6	0.6	2.34
pH 7.0	6.41	6.94	0.53	7.64	26.0	25.3	0.7	2.77

Table 8. *PAR sensor against the reference PAR meter (provisional light source)*

Distance (mm)	Reference PAR meter	PAR sensor	Absolute difference	Percent error (%)
60	31.4	37	5.6	17.83
80	39.8	24	15.8	39.70
110	30.6	20	10.6	34.64
130	34.3	17	17.3	50.44

Note. PAR units were not recorded with these readings; they will be stated when the fixed-lamp test is reported.

The DO sensor read high in all three trials by 0.32–0.40 mg/L. A consistent offset of this kind can be removed by recalibration, which is under way together with a firmware revision to bring all channels within 2% [20]. The pH sensor was 0.16 units off in the pH 4.0 buffer and 0.53 units off in the pH 7.0 buffer; with one reading per buffer, no standard deviation can yet be reported, so repeat readings are needed. The reference meter itself read 4.22 in the pH 4.00 buffer, so it should also be checked before further calibration. The temperature sensor read 0.6–0.7 °C high, close to the DS18B20's rated accuracy of ± 0.5 °C.

The PAR comparison used a phone flashlight as a provisional source, and the reference reading did not fall consistently with distance; it will be repeated with a fixed lamp. The CO₂ sensor currently samples ambient air, so it reads about 400 ppm; it is being moved to a dry sampling chamber on the exhaust gas line, with a water trap and filter [20]. Water level and turbidity have been given initial calibrations, and their readings will be reported with the reactor runs.

3.2 Flask Cultivation of *Scenedesmus quadricauda*

Two acclimatization runs were grown in 500 mL flasks in BG11 medium under purple LED light of about 10,000 lux. Run 1 was inoculated on 27 August 2026, with salinity raised from 0 to 1 ppt on day 16. Run 2 was inoculated on 14 September 2026, with salinity raised to 2 ppt on day 8

and 3 ppt on day 16. Absorbance at 750 nm was converted to dry biomass with the standard curve in Table 9.

Table 9. *Standard curve for S. quadricauda (absorbance at 750 nm against dry weight)*

Dilution	Measured A750	Dilution factor	Corrected A750	Dry weight (mg per 15 mL)	Biomass (g/L)
7:15	0.495	1	0.495	6.09	0.406
8:15	0.527	1	0.527	8.00	0.534
10:15	0.812	1	0.812	11.12	0.741
12:15	0.894	1	0.894	11.94	0.796
No dilution	0.947	1.5	1.421	19.69	1.313

Note. Biomass (g/L) = $0.9264 \times A_{750} - 0.0108$; $R^2 = 0.989$, $n = 5$. The undiluted standard (15 mL of culture with no distilled water) absorbed above 1.0, beyond the range in which absorbance is proportional to concentration (Beer–Lambert law), so it was diluted 1.5-fold for reading and the reading was multiplied by 1.5; the other standards absorbed below 1.0 and were read directly.

Table 10. *Growth of S. quadricauda in 500 mL flasks*

Measure	Run 1	Run 2
Inoculated	27 Aug 2026	14 Sep 2026
Starter culture A_{750}	1.154	1.027 (pH 10.2)
Initial biomass, X_0 (g/L)	0.255	0.237
Peak biomass, $X_{\max}$ (g/L)	0.974 (day 14)	1.339 (day 22)
Specific growth rate, exponential phase (d^{-1})	0.176 (days 0–5, $R^2 = 0.9996$)	0.190 (days 0–4, $R^2 = 0.990$)
Doubling time, exponential phase (d)	3.9	3.6
Average growth rate, day 0 to peak (d^{-1})	0.096	0.079
Volumetric productivity, P_x ($g\ L^{-1}\ d^{-1}$)	0.051	0.050
pH range	7.4–10.8	8.2–10.9

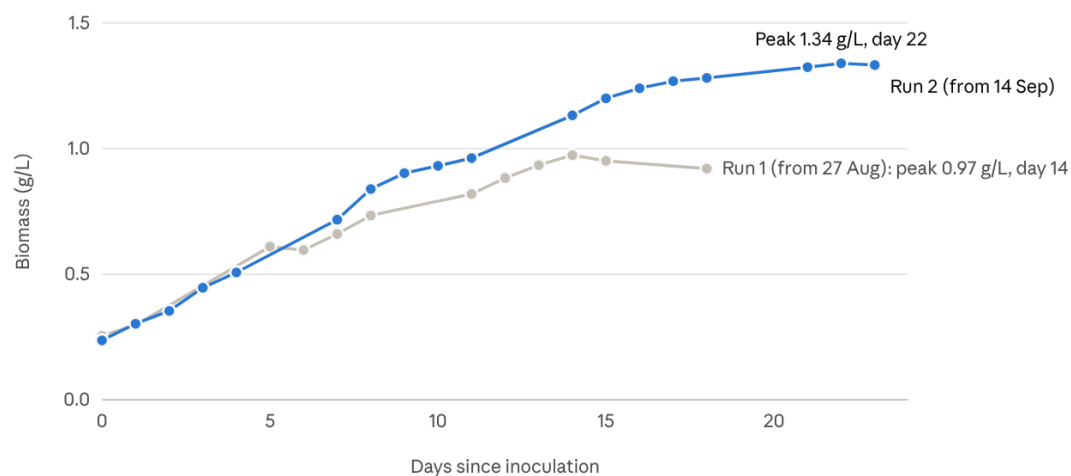
Note. The exponential-phase rate is the slope of $\ln X$ against time over the window shown. Run 1 was not sampled on days 2–4, so its fit uses three points.

Both runs grew fastest in their first four to five days, at 0.176 and 0.190 d⁻¹ (doubling times of 3.9 and 3.6 days), and then slowed (Table 10, Figure 2). Averaged from day 0 to the peak, the rates fall to 0.096 and 0.079 d⁻¹, which shows how much a whole-run average understates exponential growth. Run 2 reached a higher peak, 1.339 g/L against 0.974 g/L, and levelled off at 1.32–1.34 g/L on days 21–23, meaning it had reached stationary phase. Both runs produced about 0.05 g L⁻¹ d⁻¹. The pH rose to 10–11 in both unbuffered flasks, consistent with photosynthetic uptake of inorganic carbon [5]. Daily data are given in Appendix A.

Figure 2. Growth curves of *S. quadricauda* in two 500 mL flask runs

Run 2 kept growing to 1.34 g/L; Run 1 peaked at 0.97 g/L on day 14

Scenedesmus quadricauda in 500 mL flasks of BG11; biomass from absorbance at 750 nm (Table 9)



Scenedesmus_Quadricauda_Data.xlsx · two 500 mL flask runs, 27 Aug–7 Oct 2026

Run 1 was not sampled on days 2–4, 9–10 and 16–17; Run 2 was not sampled on days 5–6, 12–13 and 19–20.

3.3 Baseline Effluent Characterization

Before cultivation, the plant effluent was sampled on 11 June 2026 and analysed by Ostrea Mineral Laboratories [17] (Table 11). Every parameter with a printed limit was well below its

Class C effluent standard, and BOD, oil and grease, surfactants, boron, arsenic, chromium, copper, fecal coliforms and benzo(a)pyrene were below detection. The effluent is clean but nutrient-poor. Inorganic nitrogen (nitrate plus ammonia) totalled 2.27 mg/L and phosphorus 0.077 mg/L, about 0.9% and 1.1% of the 247 mg/L of nitrogen and 7.1 mg/L of phosphorus that BG11 supplies, at an N:P mass ratio of about 30:1. With so little phosphorus, nutrient balancing will largely set how much biomass the effluent can support. The low starting values also limit the removal calculation: BOD was already below its detection limit of 1 mg/L, so its removal cannot be measured, and removal of nitrogen and phosphorus will be sensitive to small analytical errors.

Table 11. *Baseline analysis of the plant effluent, sampled 11 June 2026*

Parameter	Method	Unit	Result	Class C limit
Biochemical oxygen demand (BOD)	5-day BOD test	mg/L	< 1	50
Chemical oxygen demand (COD)	Open reflux	mg/L	20	100
Nitrate as NO ₃ -N	Colorimetric, brucine	mg/L	1.60	14
Ammonia as NH ₃ -N	Ammonia-selective electrode	mg/L	0.67	4
Phosphate as P (total, reactive)	Stannous chloride	mg/L	0.077	4
Sulfate (SO ₄ ²⁻)	Turbidimetric	mg/L	10	550
Total suspended solids (TSS)	Gravimetric, dried at 103–105 °C	mg/L	13	100
Oil and grease	Liquid–liquid partition, gravimetric	mg/L	< 1.0	5
Surfactants (MBAS)	Anionic surfactants as MBAS	mg/L	< 0.10	15

Parameter	Method	Unit	Result	Class C limit
Boron	Carmine	mg/L	< 1.000	4
Arsenic	ICP-OES	mg/L	< 0.010	0.04
Chromium	ICP-OES	mg/L	< 0.010	—
Copper	ICP-OES	mg/L	< 0.002	1
Thermotolerant (fecal) coliforms	Multiple-tube fermentation (SMEWW 9221E)	MPN/100 mL	< 1.8	400
Benzo(a)pyrene	Gas chromatography–mass spectrometry	µg/L	< 0.30	3

Note. From the certificate of analysis for samples WM-031194 and WM-031195 [17]. Limits are the Class C effluent standards of DENR Administrative Orders 2016-08 and 2021-19 as printed on the certificate; no limit is printed for chromium. “<” marks a result below the method detection limit. Carbonates were not analysed.

3.4 Pending Results

The following results will be added as the data become available:

- Turbidity standard curves against OD₇₅₀ and dry weight, for both organisms and both media.
- Calibration readings for the CO₂, water-level and turbidity sensors; repeat pH and temperature readings for standard deviation; and the fixed-lamp PAR test.
- The 2 L reactor runs, beginning October 2026: logged parameter profiles, diurnal pH and DO oscillations, growth descriptors, and the analysis described in Section 2.6.
- Effluent analysis after cultivation, the carbonate results, and percent removal of each constituent against the June 2026 baseline (Section 3.3).
- The 20 L scale-up runs and the comparison of sensor readings across scales.

4. Conclusions

This proposal sets out the design of 2 L and 20 L flat-panel airlift photobioreactors and a seven-parameter monitoring system, and reports the first measurements from both. The 2 L reactor has been fabricated, and the 20 L design keeps its 50 mm light path and height-to-length ratio, though its downcomer-to-riser area ratio differs and is still to be confirmed. None of the

sensor channels tested so far meets the 2% accuracy target: temperature, pH and dissolved oxygen showed errors of 2.6–7.8% against their reference instruments, the dissolved-oxygen error is a consistent offset that recalibration can remove, and the PAR channel cannot be judged until it is tested under a fixed lamp.

In flasks, *S. quadricauda* grew at 0.18–0.19 d⁻¹ during its exponential phase and reached 1.34 g/L, which gives a baseline for the reactor runs. The plant effluent already meets Class C limits but holds nitrogen and phosphorus at about 1% of BG11 levels, so nutrient balancing, especially of phosphorus, will decide how much biomass it can support. The analysis scripts are ready to process the reactor data as they arrive. The planned runs will describe growth at their set points; finding the best operating levels will require further runs at several set points of temperature, pH and light.

On completion, the study is expected to deliver:

- Design and fabrication of 2 L and 20 L flat-panel photobioreactors for cultivation of *Nannochloropsis* and *Scenedesmus* cultures.
- A validated, calibrated seven-parameter real-time sensor monitoring system for flat-panel airlift photobioreactors, extending the inherited five-sensor baseline with logged PAR and turbidity.
- Standard calibration curves for the turbidity–optical density relationship for both *Nannochloropsis* sp. and *Scenedesmus quadricauda* cultures.
- A quantitative characterization of sensor performance, drift, and optical-sensor fouling across a modified culture medium and pretreated industrial wastewater effluent.
- Baseline process-variability and diurnal-oscillation profiles usable for monitoring and alert-threshold setting for *Nannochloropsis* sp. and *Scenedesmus quadricauda*.
- A documented, low-cost IoT monitoring platform (schematic, PCB, enclosure, and dashboard) demonstrated in both a high-value marine cultivation and a real wastewater-treatment application at the plant facility.
- A reproducible Python analysis pipeline that computes calibration statistics and growth descriptors from the logged data, shows how the parameters relate, and estimates the best temperature, pH and light levels wherever the runs span them.

5. Declaration

5.1 Source of Funding

[To be added: the organization(s) that funded the study or provided materials, equipment, facilities and third-party laboratory testing.]

5.2 Competing Interests

The author carried out this work during a data science internship at Comfac Corporation and declares no other competing interests. [To be confirmed.]

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Appendix A. Daily Growth Data for the Flask Runs

A750 is the mean $\pm$ SD of three readings unless marked otherwise. Biomass is calculated from the Table 9 equation.

Table A1. *Run 1, inoculated 27 August 2026*

Day	Date	A750 (mean $\pm$ SD)	Biomass (g/L)	pH
0	27 Aug	0.287 $\pm$ 0.002	0.255	7.4
1	28 Aug	0.333 $\pm$ 0.003	0.298	Not recorded
5	1 Sep	0.670 $\pm$ 0.003	0.610	10.1
6	2 Sep	0.655 $\pm$ 0.004	0.596	10.6
7	3 Sep	0.724 $\pm$ 0.004	0.660	8.2
8	4 Sep	0.804 $\pm$ 0.004	0.734	9.1
11	7 Sep	0.896 $\pm$ 0.006	0.819	10.7
12	8 Sep	0.964 $\pm$ 0.004	0.883	8.5
13	9 Sep	1.020 $\pm$ 0.007	0.934	9.3
14	10 Sep	1.063 $\pm$ 0.006	0.974	10.2
15	11 Sep	1.039 $\pm$ 0.007	0.951	10.4
18	14 Sep	1.005 (single reading)	0.920	10.8

Table A2. *Run 2, inoculated 14 September 2026*

Day	Date	A750 (mean $\pm$ SD)	Biomass (g/L)	pH
0	14 Sep	0.268 (single reading)	0.237	8.2
1	15 Sep	0.339 $\pm$ 0.009	0.303	8.9
2	16 Sep	0.394 $\pm$ 0.005	0.354	9.4
3	17 Sep	0.493 $\pm$ 0.004	0.446	10.4
4	18 Sep	0.559 $\pm$ 0.006	0.507	10.8
7	21 Sep	0.786 $\pm$ 0.007	0.717	9.5
8	22 Sep	0.917 $\pm$ 0.003	0.839	10.6
9	23 Sep	0.986 $\pm$ 0.007	0.902	8.8
10	24 Sep	1.017 $\pm$ 0.006	0.931	9.7
11	25 Sep	1.050 $\pm$ 0.006	0.962	10.4
14	28 Sep	1.234 $\pm$ 0.012	1.132	10.1
15	29 Sep	1.307 $\pm$ 0.007	1.200	8.6
16	30 Sep	1.350 $\pm$ 0.014	1.240	9.7
17	1 Oct	1.380 $\pm$ 0.009	1.268	10.5
18	2 Oct	1.394 $\pm$ 0.004	1.281	10.9
21	5 Oct	1.441 $\pm$ 0.007	1.324	9.6
22	6 Oct	1.457 $\pm$ 0.006	1.339	10.3
23	7 Oct	1.449 $\pm$ 0.009	1.332	10.7