

Article

Using Microalgae to Convert Brewery Carbon Gas Emissions into Valuable Bioproducts

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Abstract: The brewing industry is a major part of the agri-food sector, but its fermentation processes contribute significantly to global CO₂ emissions, exacerbating the greenhouse gas crisis. Achieving net-zero emissions requires innovative solutions, and this study explored one such solution by using microalgae to capture CO₂ from a brewery while simultaneously generating valuable bioproducts. Two microalgae species, *Tetrademus obliquus* and *Limnospira maxima*, were cultivated in a 1000 L raceway and a 400 L tubular photobioreactor, both powered by the brewery's CO₂ waste gas. The specific growth rates reached 0.3 in the raceway and 0.4–0.5 in the photobioreactor for both species. Notably, *L. maxima* showed higher productivity, achieving up to 0.80 g L⁻¹ day⁻¹ in the photobioreactor and 0.5 g L⁻¹ day⁻¹ in the raceway. Operating across 300 brewing days per year, a single module (1400 L) of this system could reduce a brewery's CO₂ emissions by 29%. These low-maintenance systems are modular, allowing for easy scaling and operation. The harvested biomass was nutritionally valuable; *L. maxima* contained up to 55% protein and 3% phycocyanin, while *T. obliquus* was rich in carbohydrates (36%) and lipids (12%), levels suitable for feeds and fertilizers. A cost-benefit analysis suggests that coupling CO₂ removal with bioproduct generation supports a sustainable circular economy while offering financial returns.



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1. Introduction

In response to the growing climate crisis, there have been international movements toward a circular economy and carbon reduction [1], and the UK government has the ambition to achieve “net-zero” carbon emissions across all sectors by 2050 [2]. This requires industries to become more energy-efficient and less carbon-intensive or to implement technologies to mitigate emissions. As one of the largest agri-food industries, the brewery industry is worth over USD 500 billion globally [3]. The UK brewery industry has a sales value of over GBP 3 billion per year, and the number of breweries has more than doubled in the past decade (source: Office of National Statistics, <https://www.ons.gov.uk>, accessed on 1 October 2024). In addition to domestic consumption, the UK's beer exporting ranks as the sixth largest in the world (source: UN Comtrade, <https://comtradeplus.un.org/>, accessed on 1 October 2024). The brewing process produces a large amount of CO₂, which must be released to avoid pressure build-up inside the fermenters. Without treatment, this waste gas would add to the ongoing climate crisis. To reduce the industry's carbon footprint, suitable treatment of this waste gas is urgently needed.

Traditionally, CO₂ capture technologies have focused on chemical and physical methods, which often require high energy consumption and costs. In contrast, a biological approach can harness natural carbon fixation and convert CO₂ into valuable bioproducts.

Microalgae are particularly suited for this purpose. They have high growth rates and can capture CO₂ efficiently via photosynthesis. Thanks to their microscopic size and simple life cycle, they can be cultivated in compact and modular systems. Two of the common system configurations are the photobioreactor and open raceway, both of which are sold prefabricated or can be constructed easily. A photobioreactor comprises a series of transparent tubes arranged either horizontally or vertically, which are connected to a pump that circulates the algal culture within a closed loop (Figure 1). Due to the enclosed nature of photobioreactors, there is a reduced risk of contamination or spillage, allowing for more precise monitoring and regulation of growth conditions. In contrast, a raceway is an open-top horizontal system in which the algal culture is circulated by a paddle wheel (Figure 1). While raceways are simpler to operate and maintain compared with photobioreactors, their open design makes them more susceptible to contamination, spillage, and variable growth conditions.



Figure 1. Horizontal tubular photobioreactor (400 L capacity (left)) and raceway (1000 L capacity (right)) installed inside of a polytunnel. Both systems received CO₂ waste gas from the brewery on site (source: A. Silkina, personal photos).

Despite the promising potential of photobioreactors and raceways for CO₂ capture and biomass production in algal cultivation, past studies have primarily focused on the technical feasibility and operational efficiency of these systems in a controlled (laboratory) environment, and there is a lack of data on the long-term economic viability and scalability of integrating these systems with industrial CO₂ emissions. A few studies have investigated remediation of brewery wastes with algae [4,5] However, those studies were mainly laboratory based and lacked onsite experimental data. Additionally, there has been limited research on the optimization of specific algal strains for enhancing bioproduct yields under variable environmental and industrial conditions. Further investigation is needed to address these knowledge gaps, particularly through large-scale, real-world trials to provide more robust data on the environmental benefits, cost-effectiveness, and sustainability of using photobioreactors and raceways for CO₂ mitigation and bioproduct development.

We conducted a feasibility study on site at a local brewery in Wales, UK to use waste CO₂ gas to grow microalgae and produce valuable bioproducts. This allowed us to assess the real-world applicability of the approach beyond theoretical and laboratory-scale studies. We tested the two common system configurations: a photobioreactor and a raceway. For the reason that the waste gas from the brewing process is non-toxic, the produced microalgal biomass can be harvested for downstream processing to develop safe and useful products. There are existing markets for algal-based fertilizers, animal feeds, nutraceuticals, and pharmaceuticals [6,7]). It is therefore possible to select strains of microalgae to couple CO₂ removal and bioproduct development according to the specific conditions and requirements.

This will decrease CO₂ emissions on the one hand and create a new revenue stream on the other, thereby promoting a circular economy.

For this project, we selected the algal species *Limnospira* (*Spirulina*) *maxima* and *Tetradescmus* (*Scenedesmus*) *obliquus* based on considerations of the growth rate, CO₂ capture potential, marketability for downstream processing, and adaptability for other industries. The freshwater cyanobacterium genus *Limnospira* can tolerate conditions which may be harmful to other species (e.g., high temperature, high light intensity, and fluctuating pH) [8]. It is already widely used as an ingredient in animal feeds and food supplements, but it is poor in essential fatty acids such as EPA and DHA [9]. *Tetradescmus* is among the most common freshwater eukaryotic microalgal genera. It has been studied as a feed stock for biofuel production [10] and for water clean-up [11] but it has not been used for animal feeds or food supplements at the commercial scale.

By measuring the performance of the cultivation systems on site and the biochemical compositions of the resultant algal biomass, this study provided the necessary scientific data to support integrating CO₂ mitigation with bioproduct development to drive a low-carbon circular economy.

The specific objectives of this research study were to (1) assess the CO₂ capture efficiency of *L. maxima* and *T. obliquus* in both photobioreactor and raceway configurations under real-world brewery conditions; (2) evaluate the long-term economic feasibility of implementing photobioreactors and raceways on a commercial scale within the brewery industry; and (3) examine the biochemical properties of the harvested algal biomass (e.g., protein, lipid, and nutrient profiles) to assess its suitability for various commercial applications, such as animal feeds, fertilizers, and nutraceuticals, thereby advancing the circular economy.

2. Materials and Methods

2.1. Bluestone Brewery and Test Site

Bluestone, a UK-based microbrewery in Cilgwyn, Pembrokeshire (SA42 0QW), produces 120,000–150,000 L of beer between the months of March and December (~300 days). The brewing process generates approximately 4 kg of CO₂ per 100 L of beer, 3 kg of which is used for carbonization of the beer, while the remaining 1 kg is discharged. In total, the brewery releases 1200–1500 kg CO₂ y⁻¹.

The algal cultivation systems were set up inside a polytunnel on an open field adjacent to the brewery (Figure 1). The polytunnel was made of transparent plastic sheets, and the tunnel entrances were left open to aid ventilation. A Phycopond™ open raceway (RW; 1000 L) and a Biofence™ closed photobioreactor (PBR; 400 L), both from Varicon Aqua (Worcester, UK) (<https://www.variconaqua.com/>, accessed on 1 October 2024), were installed and connected via tubing to the CO₂ gas discharge port in the brewery. The CO₂ supply tubes were connected with a flow meter to the PBR and added at a low rate (10%) continuously to the PBR and RW. The concentration of CO₂ of 97–107% (97,963–1,077,112 ppm) was directly measured with a portable gas chromatograph equipped with a flame ionization detector (GC-2010, Shimadzu, Kyoto, Japan).

The experiments were performed in July–December 2022 with *T. obliquus* and March–August 2023 with *L. maxima*, growing the algae in a semi-continuous way of cultivation. During cultivation, the ambient temperature ranged from 13 to 22 °C.

2.2. Algal Species

Seed cultures of *T. obliquus* (CCAP 276/6A) and *L. maxima* (CCAP 1475/9) were originally obtained from the CCAP culture collection in the UK and maintained routinely at Swansea University. For this study, both species were first grown in a laboratory under a temperature of 18 °C and illumination of 100 μmol photons m⁻²s⁻¹ on a 16 h light and 8 h dark cycle. F/2 and *Spirulina* standard media as well as SP media based on modified Zarrouk media premixes, both provided by Varicon Aqua (<https://www.variconaqua.com/products-services/algal-nutrients-and-culture-media/>, accessed on 1 October 2024),

were used to maintain stock cultures of *T. obliquus* and *L. maxima*, respectively. These media were evaluated across different cultivation scales, including laboratory-scale flask experiments, medium-scale set-ups (up to 20 L), and large-scale cultivation (1000 L) at Swansea University facilities, with all experiments conducted at a concentration of 1 g L^{-1} . The decision to use these media, provided as premade mixtures, was made due to their ease of preparation, which was crucial given the constraints of industrial cultivation and the lack of laboratory facilities at the brewery site. This choice of media was further supported by prior research [12,13] and the high productivity of algae cultivation observed under laboratory and scaled-up conditions at the university.

When the stock cultures reached the exponential growth phase, the aliquots were transported to the brewery site to inoculate the PBR and RW.

2.3. Preparation of Photobioreactor and Raceway Systems

Before the experiments, the systems were filled with tap water, disinfected with sodium hypochlorite (0.5 mL L^{-1}), and then neutralized by sodium thiosulfate (0.01 mg L^{-1}). After chemical sterilization, concentrated nutrients in powder form (F/2 for *T. obliquus* and Spirulina standard media for *L. maxima*) and algal inocula (enough to reach $0.5 \text{ OD}_{750\text{nm}}$ (10% of the system volume)) were added to the PBR and RW. After the inoculation, samples were taken for various measurements as explained below.

2.4. Sampling and Measurements

Aliquots of 50 mL were taken from the systems daily to measure the pH and T ($^{\circ}\text{C}$) on site. The aliquot samples were then frozen and returned to the university. In the laboratory, the samples were slowly thawed and used for various measurements.

Optical density (OD_{750}): Cell abundance was measured as the optical density at a wavelength of 750 nm using a spectrophotometer (SPECTROStar Nano de BMG Labtech, Ortenberg, Germany).

Dry weight: A dry pre-combusted filter (Whatman 47 mm GF/C) was weighed (W_1). A known volume of the sample (V ; 10 mL) was then passed through the filter, and any algal residuals were washed with 10 mL water and added to the filter. The filter was dried in an oven for 24 h and weighed again (W_2). The volumetric algal dry weight was then calculated as $X (\text{g L}^{-1}) = (W_2 - W_1)/V$.

Specific growth rate (μ): This was calculated as the change in algal biomass over a particular time interval such that $\mu = (\ln(X_2/X_1))/(t_2 - t_1)$, where X_2 and X_1 are dry weights and t_2 and t_1 are the corresponding days.

Volumetric productivity (P): Volumetric productivity was calculated as the maximum production of algal dry mass divided by the corresponding number of days.

CO_2 removal: Via photosynthesis, microalgae consume CO_2 while producing biomass. Under normal autotrophic conditions, microalgae consume 1.8–2.2 kg CO_2 per kg of biomass produced [5,14,15]. In our research, we measured the 47% carbon cell concentration (with the elemental analyzer method described by Mayers et al. (2013) [16] for *Tetradismus* and *Limposira* per cell. Based on the 10% rate of known concentration gaseous CO_2 injection, the conversion rate was 2.12 kg CO_2 per 1 kg of algae. Based on this and the related volumetric productivity and number of days of brewery operation (300 days per year), the total annual CO_2 removal was estimated.

Nutrients uptake: To measure the dissolved nutrients, a 25 mL aliquot was centrifuged at 4700 rpm for 10 min (Allegra X-30R Centrifuge, Beckman Coulter, Mumbai, MA, USA). The supernatant was then filtered through a $0.2 \mu\text{m}$ membrane. The filtrate was used for measuring nitrate (NO_3^-) and phosphate (PO_4^{3-}) ions based on colorimetric reactions using reagent kits (Spectroquant[®], Merck KGaA, Darmstadt, Germany) [17]. The absorbance of the treated samples was measured at 345 nm for the nitrates and 410 nm for the phosphates on the spectrophotometer (SHIMADZU UV-2600, Kyoto, Japan) and then converted to concentrations based on the respective calibration curves, which were prepared with the standard chemicals.

2.5. Harvesting Procedure and Post-Harvesting Analysis

The PBR and RW systems were run until the algal populations reached a stationary state or were entering the senescent phase, and then the cultures were transferred into large plastic containers and returned to the laboratory. The algal biomass was concentrated using a membrane filtration system at Swansea University as described earlier [13]. The concentrated biomass was centrifuged at a temperature of 10 °C at 12,800× g using a Beckman J2-21M/E centrifuge with a JA 10 rotor (Beckman, Brea, CA, USA). Each batch was suspended and washed twice with deionized water. The collected biomass was frozen at −80 °C and then freeze-dried (Edwards Modulyo Freeze Dryer, Burgess Hill, UK). The bulk biochemical compositions (percentages of carbohydrates, lipids, and proteins) were analyzed via FTIR [16,18]. This method was calibrated previously with the standard extraction methods for the main biochemical groups using a multi-assay procedure, which was described by Fuentes-Grünewald et al. (2021) and Kapoore et al. (2019) [19,20].

L. maxima is known to contain the high-value pigment phycocyanin [21]. We therefore extracted phycocyanin from the harvested *L. maxima* biomass for 3–20 °C freeze-thaw cycles using 3 mL of 0.1 mol L^{−1} phosphate buffer (pH = 6) as a solvent for 1 mg of dry biomass [22]. The extracted phycocyanin, after centrifugation at 4700 rpm for 10 min at 4 °C, was analyzed using the equation of Beer and Eshel (1985) [23]:

$$\text{PC (mg/mL)} = [(\text{OD}_{618\text{nm}} - \text{OD}_{645\text{nm}}) - (\text{OD}_{592\text{nm}} - \text{OD}_{645\text{nm}}) \times 0.51] \times 0.15$$

where OD is the optical density measured at 615 nm, 645 nm, or 592 nm. The obtained concentration was recalculated as the percent of total biomass, which was 3% for *L. maxima* cultured in a PBR and RW. Based on the percentage values and the related volumetric productivity and duration of brewery operation (300 days per year), the total annual production of biochemicals was estimated.

2.6. Statistical Analysis

Statistical analysis was conducted in R. Crossed-factor ANOVAs were carried out after normal distribution of the data was confirmed with a Shapiro test. Tukey tests were used for post hoc comparisons. A threshold *p* value of 0.05 was used in all tests.

3. Results

3.1. Growth and Nutrient Uptake Dynamics of *Limnospira maxima*

The growth of *L. maxima* in a PBR based on OD₇₅₀ was followed for 28 days (Figure 2A). The culture did not exhibit any lag phase after inoculation. The algal population reached maximum productivity within 10 days, and it entered a stationary phase on day 15. The maximum growth rate (μ) was 0.48, giving a volumetric productivity of 0.8 g L^{−1} day^{−1} (Table 1). The growth of *L. maxima* in an RW was followed for 40 days (Figure 3A). The population showed exponential growth initially (days 1–15; $\mu = 0.3$), yielding volumetric productivity of 0.52 g L^{−1} day^{−1} (Table 1). The nutrient uptake during growth in the PBR and RW for the trials is presented in Figures 2B and 3B, respectively. Nutrient uptake was aligned with the growth dynamics, with nitrates and phosphates being absorbed proportionately with biomass accumulation. Specifically, nitrate and phosphate absorption was efficient for the first 7–10 days of cultivation for the PBR and RW, being 17 mg L^{−1} day^{−1} for nitrates and 1.4 mg L^{−1} day^{−1} for phosphates. However, other conditions were suboptimal due to the industrial site's location, resulting in relatively low productivity data. These conditions can be optimized for improved outcomes with more controlled approaches and extended trial durations.

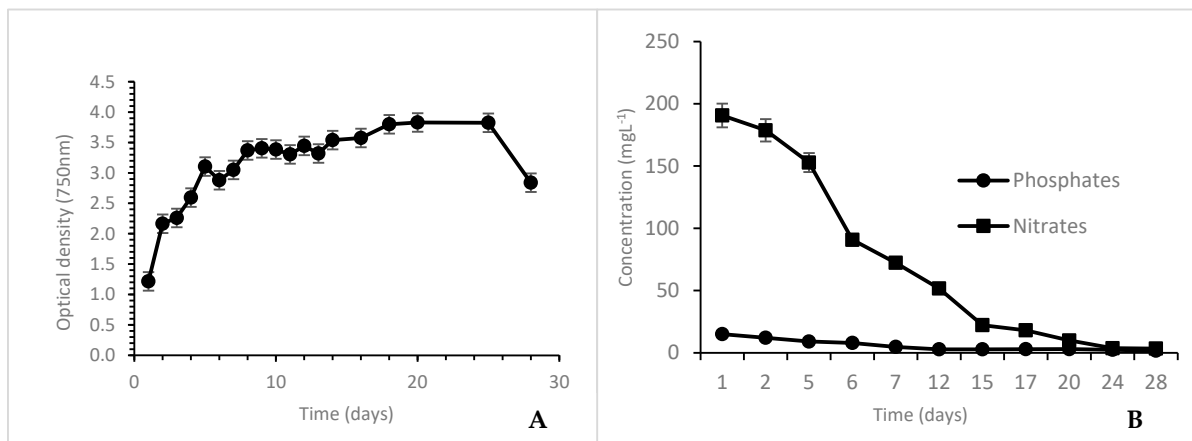


Figure 2. Growth and nutrient uptake of *Limnospira maxima* in a photobioreactor (PBR) receiving CO₂ waste gas from a local brewery on site. (A) The growth data in three biological replicates were measured using the optical density (OD) at a wavelength of 750 nm. (B) Nutrient uptake of *L. maxima* culture during the growth, measured via the nitrate and phosphate concentrations in the supernatants in three replicates.

Table 1. Estimated growth and production parameters for *Limnospira maxima* and *Tetradesmus obliquus* in photobioreactor (PBR) and raceway (RW) systems receiving CO₂ waste gas from a local brewery.

Cultivation	Maximum Growth Rate (d ⁻¹)	Volumetric Productivity (g L ⁻¹ day ⁻¹)	Total Biomass Harvest per 300 Days (kg)	Total CO ₂ Removal per 300 Days (kg)	Total Protein per 300 Days (kg)	Total Phycocyanin per 300 Days (kg)
<i>Limnospira maxima</i>						
400 L PBR	0.48	0.8	96	211.2	46	6.3
1000 L RW	0.3	0.52	156	343.2	84.2	10.3
<i>Tetradesmus obliquus</i>						
400 L PBR	0.43	0.48	57.6	126.72	21.8	n/a
1000 L RW	0.28	0.32	96	211.2	31.6	n/a

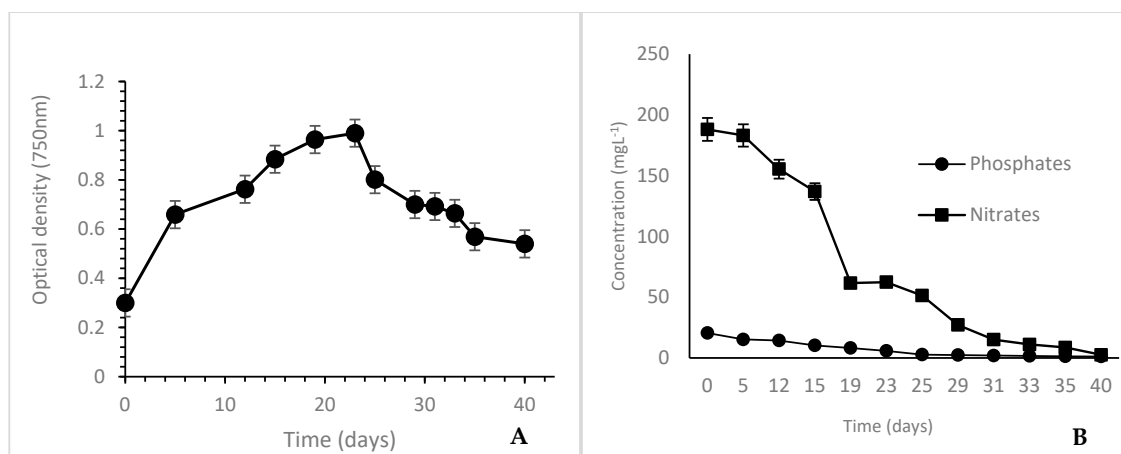


Figure 3. Growth and nutrient uptake of *Limnospira maxima* in a raceway receiving CO₂ waste gas from a local brewery on site. (A) The growth data in three biological replicates were measured via the optical density (OD) at a wavelength of 750 nm. (B) Nutrient uptake of *L. maxima* culture during the growth, measured with the nitrate and phosphate concentrations in the supernatants in three replicates.

3.2. Growth and Nutrient Uptake Dynamics of *Tetradismus obliquus*

The growth of *T. obliquus* in the PBR was observed for 40 days (Figure 4A). The culture grew rapidly in the first 23 days with a specific growth rate (μ) of 0.43. The corresponding volumetric productivity was $0.48 \text{ g L}^{-1} \text{ day}^{-1}$ (Table 1).

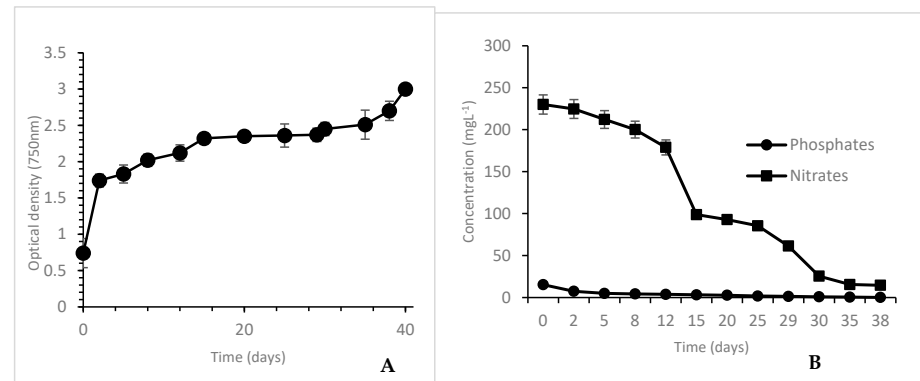


Figure 4. Growth and nutrient uptake of *Tetradismus obliquus* in the PBR receiving CO₂ waste gas from a local brewery on site. (A) The growth data in three biological replicates were measured using the optical density (OD) at a wavelength of 750 nm. (B) Nutrient uptake of *L. maxima* culture during the growth, measured via the nitrate and phosphate concentrations in the supernatants in three replicates.

The growth of *T. obliquus* in the RW was followed for 35 days (Figure 5A). The maximum growth rate was attained within the first 11 days ($\mu = 0.43$), where the corresponding volumetric productivity was $0.32 \text{ g L}^{-1} \text{ day}^{-1}$ (Table 1). The nutrient uptake during the growth of *T. obliquus* is presented in Figure 4B for the PBR growth and Figure 5B for the RW growth. In the PBR, nutrients were slower during the first 10 days but then accelerated, resulting in an average nitrate uptake rate of $8.6 \text{ mg L}^{-1} \text{ day}^{-1}$. Phosphate absorption, on the other hand, occurred gradually and in proportion to the PBR growth of *Tetradismus* throughout the cultivation period, and it was $0.9 \text{ mg L}^{-1} \text{ day}^{-1}$. In the RW culture, nitrate uptake exhibited a rapid phase during the first 5 days, with a rate of $12 \text{ mg L}^{-1} \text{ day}^{-1}$. This was followed by slower uptake over the next 10 days before increasing again toward the end of the experiment. On average, the nitrate uptake rate was $5.2 \text{ mg L}^{-1} \text{ day}^{-1}$. This pattern suggests potential for optimization in nutrient availability to sustain consistent biomass production throughout the cultivation period. The phosphate uptake was constant during the RW growth, with an average rate of $0.75 \text{ mg L}^{-1} \text{ day}^{-1}$ (Figure 5B).

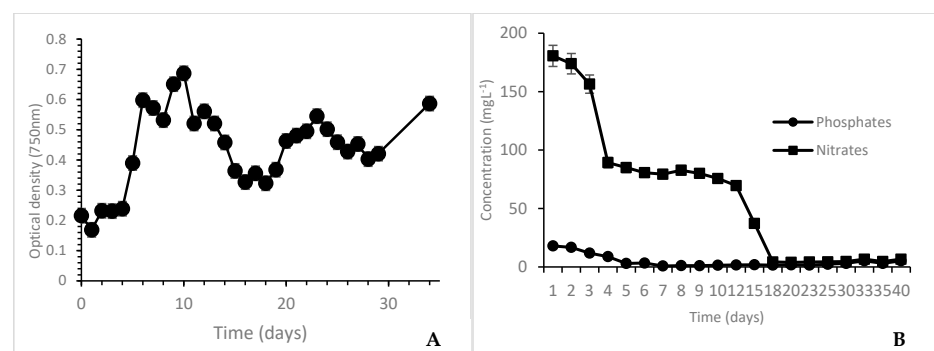


Figure 5. Growth and nutrient uptake of *Tetradismus obliquus* in a raceway receiving CO₂ waste gas from a local brewery on site. (A) The growth data in three biological replicates were measured using the optical density (OD) at a wavelength of 750 nm. (B) Nutrient uptake of *T. obliquus* culture during the growth, measured using the nitrate and phosphate concentrations in the supernatants in three replicates.

3.3. Biochemical Compositions

Harvesting of the biomass was performed when the cultures reached a stationary phase; *T. obliquus* was at an OD_{750nm} of 2.5 for the PBR and 0.6 for the RW, while *L. maxima* was at an OD of 3.5 for the PBR and 0.8 for the RW. The biomass biochemical compositions of the two species grown in the PBR and RW are presented in Figure 6. The *L. maxima* biomass contained 48–55% proteins, 27–28% carbohydrates, 5% lipids, and 3% phycocyanin, while the compositions were not significantly different ($p < 0.05$) between the two cultivation systems. The *T. obliquus* biomass contained 33–38% carbohydrates and proteins and ~11.8% lipids without significant differences ($p < 0.05$) between the two systems.

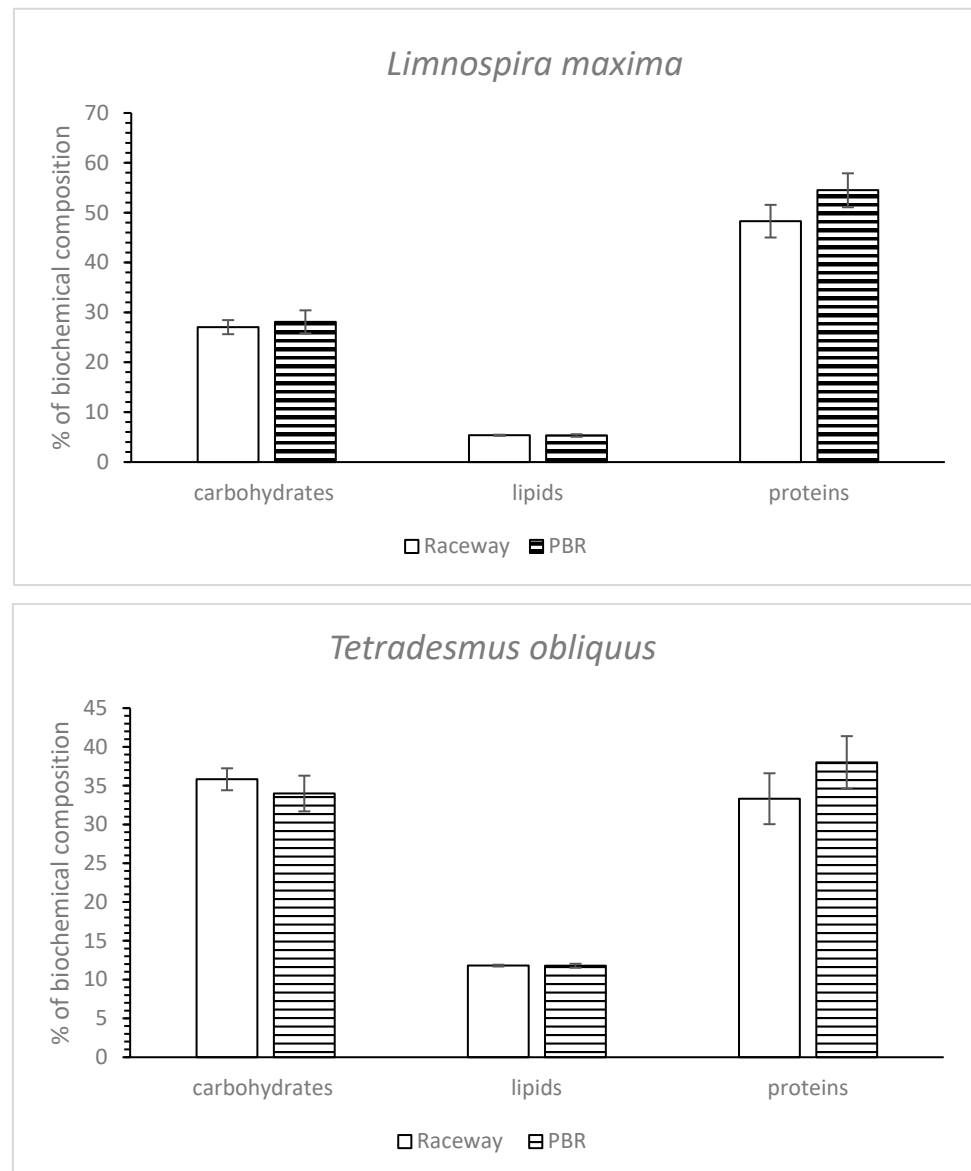


Figure 6. Biochemical compositions of two algal species grown in a raceway and photobioreactor receiving CO₂ waste gas from a local brewery on site. The *L. maxima* biomass also contained 3% phycocyanin.

4. Discussion

To achieve net-zero carbon emissions, nations must consider a multi-pronged approach to lowering greenhouse gas emissions. For energy-intensive sectors, transitioning to renewable alternatives is a much-needed solution, such as solar, wind, and marine renewable energies [24]. For the food and drink industries, switching to more energy-efficient

machinery and processes is an option [25]. In the case of breweries, however, CO₂ production is an integral part of the biological reaction in brewing (i.e., there is no alternative to fermentation which would exclude releasing CO₂). Therefore, for the brewery industry to achieve net-zero emissions, it needs to consider post-brewing capture of CO₂.

Different CO₂ capture technologies exist, from chemical “scrubbing” [26] to biological uptake [27,28]. While biological methods tend to work more slowly than chemical methods, they produce biomass which may create additional revenue streams. This is a particularly attractive option for breweries, where the waste CO₂ gas from the brewing process tends to be free of harmful substances, thereby increasing the recycle and reuse values of the biomass. By using “market-accepted” microalgal genera, such as *Limnospira* (*Spirulina*) and *Tetradismus* (*Scenedesmus*), it is possible to couple CO₂ capture and the production of bioproducts for high-value markets. For this to work, CO₂ from the brewery must be captured on site. Another consideration is that microbrewers are unlikely to invest much time and resources to maintain and regulate the systems. Therefore, it is important to test the performance of the systems with minimal intervention.

Here, we tested two microalgal culture systems for capturing CO₂ from a small local brewery. Both PBRs and RWs are available commercially and can be installed in modules to suit the land footprint and size of a brewery. Other than the initial system preparation, inoculation, and harvesting, the operation was essentially care-free. We were able to culture both *L. maxima* and *T. obliquus* in both systems on site using CO₂ waste gas from the brewery. The maximum growth rates were less than the typical one (doubling per day) under ideal conditions ($\mu = 0.69 \text{ d}^{-1}$), but they were comparable to the growth of *Tetradismus* ($\mu = 0.5 \text{ d}^{-1}$) and *Limnospira* (0.35 d^{-1}) with intensive CO₂ or biogas [29,30]. The less-than-ideal growth rate was to be expected due to the fluctuation of ambient light and variable and suboptimal temperature conditions at the brewery site. Additionally, optimizing the uptake of other macronutrients will be necessary, as the current results highlight the importance of maximizing nutrient uptake efficiency to achieve more consistent biomass production throughout the cultivation period. Adjusting the timing and concentration of nutrient inputs, especially for *Tetradismus* culture, could help maintain higher uptake rates during slower phases, ensuring a continuous supply of essential macronutrients for growth. Such improvements in nutrient management could increase the overall efficiency of the cultivation system, ultimately leading to higher biomass yields and more robust productivity. Nevertheless, the algal biomass accumulated to levels orders of magnitude higher than typical algal blooms observed in nature (e.g., [31]) and other biogas or intensive CO₂ studies [15,30], suggesting that our PBR and RW set-ups were appropriate for mass-producing algae.

Because the two species were used at different times of the year, we were unable to directly compare the growth parameters between them. However, between the two systems, both species had better yields in the PBR, likely because the closed PBR system provided a more stable growth environment than the open RW system. Nevertheless, the biomass levels were still much lower than what could be attained under highly regulated growth conditions (e.g., [32]), reflecting the limitations of the low-maintenance approach we used. Using only one module for each system type (PBR or RW with a total volume of 1400 L), we estimated that *L. maxima* could remove 211–343 kg CO₂ y^{−1} and *T. obliquus* could remove 127–211 kg CO₂ y^{−1}. This is equivalent to 14–29% y^{−1} (*L. maxima*) and 8–18% y^{−1} (*T. obliquus*) of the CO₂ emissions from a brewery. The space required per module was small (Figure 1), and one could easily connect multiple modules to increase the total CO₂ removal.

In addition to removing CO₂, the algal biomass produced from this simple approach contained valuable biochemicals for downstream applications. For example, we showed that the harvested *T. obliquus* biomass contained large amounts of carbohydrates (35%) and lipids (12%), which would be useful for biofuel and bioenergy production [33,34]. Similar results were demonstrated when *T. obliquus* was grown in the control laboratory conditions [35]. The *L. maxima* biomass contained high protein contents which would be

suitable for animal feed [36]. Additionally, it contained the high-value pigment phycocyanin for nutraceuticals [37,38]. In earlier studies [5,15,39], the *Limnospira* biomass had a similar biochemical composition content, but in our study, the protein percentage was higher by 1.5 times.

Despite the simplicity of the approach, a wider adoption of PBRs or RWs by industries requires a more nuanced consideration of the financial implications. For our local micro-brewery, the main brewing period lasts about 300 days per year. PBR and RW systems have a life span of about 20 years before substantial repair or replacement is needed. Using our results for *L. maxima*, we estimated the costs and benefits as follows (Table 2). The yearly financial cost included the average cost of the PBR or RW module and the operational costs (electricity, consumables, transportation, and downstream processing). The yearly financial benefit included savings in terms of CO₂ removal based on the UK Emission Trading Scheme, protein production, and phycocyanin production. This cost-benefit analysis should be viewed as a rough guide because the price of electricity, carbon emissions, and bioproducts all may fluctuate. Nevertheless, our calculations suggest that growing *L. maxima* in a PBR (one 400 L module) would produce a lower financial return than the cost, whereas growing *L. maxima* in an RW (one 1000 L module) may generate a net financial gain. A major determining factor is the high-value product, which could easily tip the balance toward a net gain. While in this study we used phycocyanin as an example, the algal biomass may contain other high-value compounds for commercial exploitations, such as antioxidants, vitamins, and essential fatty acids [37]. In practice, the brewery may lack the resources or expertise to develop algal products. Instead, they may partner with bioproduct companies, who may share the cost and exploit the algal biomass produced at the brewery site.

Table 2. Cost-benefit estimates for growing *Limnospira maxima* in PBR or RW using CO₂ waste gas from a local brewery. Both the cost and benefit were calculated for a production period of 300 days per year. Hardware cost was calculated based on a 20-year lifespan of PBR and RW.

	PBR	RW
COST (GBP per year)		
Hardware (incl. polytunnel)	925	325
Operation (electricity, consumables, transportation, downstream processing)	1100	900
Total Cost	2025	1225
BENEFIT (GBP per year)		
CO ₂ removal ¹	12.25	19.92
Biomass (protein) ²	57.5	105.3
High-value product (Phycocyanin) ³	1147	1874
Total Benefit	1217	1999

¹ Based on UK ETS scheme, which was GBP 58.03 per ton of CO₂-eq on 27 June 2023 (source: <https://ember-energy.org/>, <https://ember-climate.org/data/data-tools/carbon-price-viewer/>) accessed on 1 October 2024. ² Animal feed market price of GBP 1.25 per 1 kg of protein (source: <https://www.gov.uk/government/statistical-data-sets/animal-feed-prices>), accessed on 1 October 2024. ³ Phycocyanin market price of GBP 182 per 1 g based (source: Sigma-Aldrich, St. Louis, MO, USA; <https://www.sigmaaldrich.com/GB/en/product/sigma/52468>) accessed on 1 October 2024.

For the brewery itself, another consideration is potential added benefits via “green marketing”. Research has found that while many customers claim they want environmentally friendly products, few switch their buying preferences, creating an “intention-action gap” [40]. In our example, the PBR or RW operation does not interfere with the brewing process itself, and the beer quality remains unchanged. Therefore, the brewery owner can raise the image of their products by highlighting the environmentally responsible

brewing process but without changing the characteristics of the product itself. This can be an effective way to bridge the “intention-action gap” and boost sales. Future prospects for this project include investigating brewery wastewater as a nutrient source for algal growth, further closing the loop for algal production and reducing environmental impact and operational costs. Additionally, developing a lifecycle analysis (LCA) model for this integrated approach would provide breweries with data to make informed decisions about adopting circular economy practices.

5. Conclusions

We showed that photobioreactor (PBR) and raceway (RW) systems could be easily installed and operated on site at a local brewery to capture waste CO₂ gas from the brewing process and produce algal biomass for downstream extraction of valuable products, thereby promoting a more sustainable circular economy. While we deliberately kept the system maintenance to a minimum to suit a microbrewery, larger operators with more resources may boost algal production by regulating the growth conditions (e.g., nutrients, light, temperature, and pH) more closely. In this study, we tested two algal species. Other species can be considered based on their growth characteristics and market potentials. While we focused here on CO₂ emissions, breweries also produce other waste streams, including spent grains and wastewater [41]. With the appropriate pre-treatment, spent grains and brewery wastewater can also be used to cultivate microalgae [42], adding to the overall waste reduction and valorization [43]. Likewise, extraction of other high-value compounds will also add to the overall economic benefits.

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