Optimization of advanced bio-based carbon capture and utilization system through technological development and comparison

Mariniello A., Oliva G.[1], Belgiorno V., Naddeo V., Zarra T.*

Sanitary Environmental Engineering Division (SEED) – Department of Civil Engineering, University of Salerno

*corresponding author:
e-mail: tzarra@unisa.it

Abstract Algae-based biological carbon capture and utilization (Bio-CCU) systems represent a promising approach to reduce atmospheric CO_2 concentrations while generating valuable bio-products. The study presents and investigates the optimization of an advanced algal photobioreactor (aPBR), through the development and performance comparison of different technological configurations. Three different configurations were studied and compared in terms of CO_2 capture efficiency. The configurations differ in terms of key design and operational variables. The results highlight the influence of technological aspects on key parameters of system efficiency and productivity. The CO_2 detected removal efficiencies ranged from 81% to 92%, depending on the technological setup, with the lighting system (in particular the use of purple LEDs) and the presence of a membrane-based harvesting unit emerging as the most influential variables affecting CO_2 bio-fixation performance. The research demonstrates the potential of Bio-CCU technologies to contribute to climate emergencies, circular economy objectives and bioenergy production.

Keywords: biological systems, Photobioreactor (PBR), environmental sustainability, climate change, circular economy, CO_2

1. Introduction

Climate change mitigation increasingly relies on innovative carbon capture technologies. Among these, algae-based Bio-CCU systems are gaining attention for their dual role in atmospheric CO_2 sequestration and production of high-value biomass. Unlike traditional capture and storage approaches, Bio-CCU promotes circularity through bioconversion of captured carbon into biofuels and other bioproducts (Li et al., 2023). However, technological optimization remains a major challenge, especially in closed systems such as algal photobioreactors (aPBRs), where design parameters heavily influence efficiency (Daneshvar et al., 2022). Moreover, the integration of algae-based systems with advanced oxidation processes, such as photocatalysis or ozonation, could represent a promising strategy for the removal of emerging contaminants in wastewater streams, further expanding the environmental benefits of Bio-CCU technologies (Fraiese et al., 2012). The research presents and discusses three aPBR configurations integrated within an advanced two-stage Bio-CCU system, aiming to identify the most effective design in terms of CO_2 capture.

2. Materials and Methods

2.1. Advanced Bio-CCU schematic set-up

The basic experimental set up is composed of two different units: (i) an absorption column (AC) for CO_2 transfer from gas to liquid phase; (ii) an aPBR unit inoculated with Chorella vulgaris (CCAP 211/11B), under a 12h/12h light-dark cycle. Three technological configurations of the second treatment unit (aPBR) were tested and compared (C1-C3), differing by reactor geometry, illumination system and harvesting system (Senatore et al., 2022). In particular, C1 represents a traditional cylindrical photobioreactor equipped with an aeration system based on suspended metallic diffusers, which promote mixing of the culture medium. C2 and C3, on the other hand, incorporate a self-performing membrane for algal biomass recovery, differing in their illumination systems: C3 uses purple LEDs designed to enhance photosynthetic efficiency and CO_2 bio-fixation. Experimental activities were carried out in 3 stages (30 days), increasing the liquid/gas ratio (L/G = 5, 10, 20).

2.2. Analytical methods

Key performance indicators were removal efficiency (RE), inlet load (IL) and elimination capacity (EC). The CO_2 removal efficiency (RE) was determined by measuring the CO_2 concentrations three times a day, with a GC equipped with a Thermal – Conductivity Detector (TCD). RE was estimated according to the following equation:

$$\boldsymbol{RE}\ (\%) = \frac{[\boldsymbol{CO_2}]_{\boldsymbol{in}} - [\boldsymbol{CO_2}]_{\boldsymbol{out}}}{[\boldsymbol{CO_2}]_{\boldsymbol{in}}} \cdot \mathbf{100}$$

where:
- $[CO_2]_{in}$ and $[CO_2]_{out}$ are respectively the inlet and outlet concentration of CO_2 (g m^{-3}).

CO_2 inlet load (IL) in the system, and elimination capacity (EC), which represents the CO_2 concentration removed from the system with respect to volume and in a given period, were calculated with the following equations:

$$IL\ (g\ m^{-3}h^{-1}) = \frac{([CO_2]_{in})\cdot Q_{gas}}{V} \cdot 100$$

$$EC\ (g\ m^{-3}h^{-1}) = \frac{([CO_2]_{in} - [CO_2]_{out})\cdot Q_{gas}}{V} \cdot 100$$

where:
- Q_{gas} is the gas flow rate ($m^3\ h^{-1}$);
- V (m^3) is the working volume of the photobioreactor.

3. Results and discussions

Figure 1 shows the main results obtained from the comparison of the three configurations investigated.

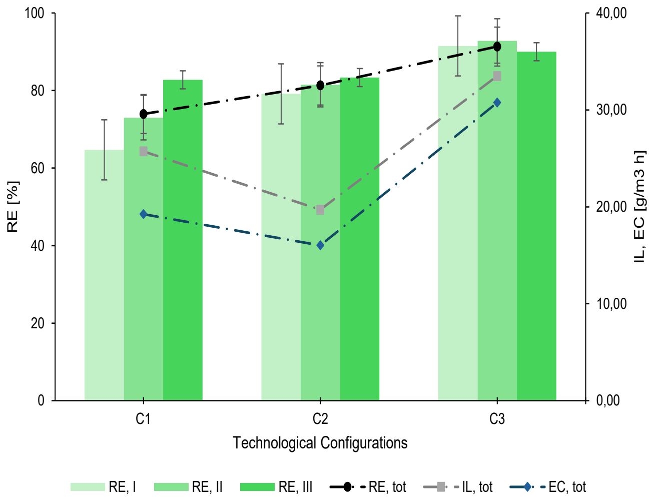

Figure 1. Efficiency removal (RE), inlet load (IL) and elimination capacity (EC).

The comparison of the three configurations across the three operational stages highlights a clear improvement in CO_2 removal efficiency (RE) from stage I to stage III for all setups. Among them, configuration C3 consistently achieved the highest RE values, exceeding 90% in the final stage and maintaining the best average performance over the entire experimental period. Notably, despite similar CO_2 inlet loads (IL) among the configurations, C3 showed a significantly higher elimination capacity (EC) with average values up to 30,76 g m^{-3} h^{-1}, nearly matching the inlet load with average values up to 33,50 g m^{-3} h^{-1}. This indicates a more efficient use of the available CO_2, likely due to the synergistic effect of purple LED lighting and membrane-based harvesting. These results confirm that specific technological improvements, especially in lighting and harvesting systems, can significantly boost CO_2 bio-fixation efficiency, even under identical operating conditions (Senatore et al., 2023).

4. Conclusion

Among the three tested configurations, C3 emerged as the most efficient and stable solution for CO_2 bio-fixation, supporting its suitability for scalable Bio-CCU systems. The use of purple LED lighting, targeting photosynthetically active wavelengths, combined with membrane-based biomass harvesting, proved to be the most effective technological elements in enhancing CO_2 removal efficiency. Experimental results show that, even under identical inlet flowrate conditions, the optimization of specific design parameters, such as illumination spectrum and harvesting strategy, can improve the overall performance of Bio-CCU systems. In view of potential full-scale applications, attention should also be given to the monitoring of possible gas-phase emissions and odour compounds that may arise during operation, as already highlighted in previous studies on environmental monitoring and odour control (Zarra et al., 2012). These findings confirm the crucial role of technological choices in maximizing the carbon capture potential of algal photobioreactors.

References

Daneshvar, E., Wicker, R. J., Show, P.-L., & Bhatnagar, A. (2022). Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization – A review. Chemical Engineering Journal, 427, 130884. https://doi.org/10.1016/j.cej.2021.130884

Li, S., Chang, H., Zhang, S., & Ho, S.-H. (2023). Production of sustainable biofuels from microalgae with CO2 bio-sequestration and life cycle assessment. Environmental Research, 227, 115730. https://doi.org/10.1016/j.envres.2023.115730

Senatore, V., Oliva, G., Buonerba, A., Zarra, T., Borea, L., Hasan, S. W., Belgiorno, V., & Naddeo, V. (2022). An integrated algal membrane photobioreactor as a green-transition technology for the carbon capture and utilization. Journal of Environmental Chemical Engineering, 10(2), 107344. https://doi.org/10.1016/j.jece.2022.107344

Senatore, V., Rueda, E., Bellver, M., Díez-Montero, R., Ferrer, I., Zarra, T., Naddeo, V., & García, J. (2023). Production of phycobiliproteins, bioplastics and lipids by the cyanobacteria Synechocystis sp. Treating secondary effluent in a biorefinery approach. Science of The Total Environment, 857, 159343. https://doi.org/10.1016/j.scitotenv.2022.159343

Z Zarra, T., Reiser, M., Naddeo, V., Belgiorno, V., & Kranert, M. (2012). A comparative and Critical Evaluation of Different Sampling Materials in the Measurement of Odour Concentration by Dynamic Olfactometry. Chemical engineering transactions, 30, pp. 307-312. https://doi.org/10.3303/CET1230052.

Fraiese, A., Naddeo, V., Uyguner-Demirel, C. S., Prado, M., Cesaro, A., Zarra, T., ... & Ballesteros Jr, F. (2019). Removal of emerging contaminants in wastewater by sonolysis, photocatalysis and ozonation. Global NEST Journal, 21, 98-105. https://doi.org/10.30955/gnj.002625.