Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (36th Cycle)

Next-Generation Microalgae Cultivation: Innovative flat panel photobioreactor with tailored light regulation and hybrid modelling approach

Summary

The quest for sustainable microalgae production necessitates the development of advanced photobioreactor (PBR) systems that address current limitations in energy efficiency, light management, and process optimization. Microalgae offer immense potential as a sustainable resource, but existing PBR systems, particularly flat panel PBRs, are hampered by high energy costs and biofouling risks associated with traditional air bubbling methods for mixing. Additionally, the reliance on compressed air significantly contributes to the PBR's overall energy consumption. This research aims to enhance the technological efficacy and sustainability of PBRs through innovative design and advanced engineering solutions.

This PhD thesis introduces an innovative flat panel photobioreactor featuring a centrifugal pump-assisted hydraulic circuit designed to overcome these challenges. This design confines microalgae within a positive-pressurized serpentine directly exposed to artificial light, optimizing light distribution and enhancing growth efficiency. The flat panels, measuring 1.3 cm in width, are a critical feature that maximizes light penetration, essential for photosynthetic activity and biomass production. The research highlights the potential of this design for energy-efficient industrial applications, particularly in CO_2 bio-fixation.

An in-depth examination of the fluid dynamics within the new PBR reveals how the centrifugal pump-assisted hydraulic circuit influences microalgae movement and interaction. By optimizing hydrodynamic performance, the system aims to uniform exposure to light, thereby enhancing microalgae productivity. A key advancement in this work is the introduction of a tuneable LED lighting engine. Composed of 10 discrete LEDs covering the entire PAR range and 2 white light LEDs, this system allows for customized light spectra tailored to the specific needs of different microalgae species. This tailored lighting approach not only enhances microalgae growth by aligning with their photosynthetic requirements but also reduces energy consumption for artificial lighting.

Additionally, achieving a balance between high volumetric productivity and high biomass concentration is essential for PBR operations. This thesis presents a hybrid model approach developed using first-principle equations to streamline computational processes and reduce the need for extensive experimental data. The model was trained and validated with batch cultivations of the red microalga *Galdieria sulphuraria*, grown under controlled conditions in the novel PBR. The precise

control over process conditions, including light management and tailored spectra, demonstrated the model's robustness in predicting growth outcomes.

Lastly, as part of this PhD work, the technical feasibility of water reuse and nutrients recovery specifically for the cultivation of the polyextremophile *G. sulphuraria* is presented. This case study aims to demonstrate how these efforts can potentially yield significant resource savings and reduce environmental impact, thereby contributing to the advancement of sustainable practices in large-scale microalgae cultivation.

Overall, this thesis makes significant contributions to the field of microalgae cultivation by presenting an advanced PBR design with e detailed description of its fluid dynamics, enhancing light management, and developing a hybrid model for process optimization. This novel flat panel photobioreactor with a centrifugal pump-assisted hydraulic circuit and tailored LED lighting system demonstrates a promising pathway toward more efficient and sustainable microalgae production. Also, this PhD thesis lays the groundwork for future works focusing on the employment and refining of hybrid models as potent engineering tools to optimize microalgae cultivation processes, as well as emphasizing the importance of the freshwater footprint to ensure environmental compliance and maximize resource efficiency.