



Research article

Shining a light on outdoor algal systems for wastewater treatment: How artificial light enhancement impacts biomass costs and life cycle

Iara Barbosa Magalhães^{a,*}, Maurino Magno de Jesus Júnior^b, Bruna Thomazinho França^c,
Thiago Abrantes Silva^a, Alexia S.A.P. Pereira^a, Lucas Cescon de Almeida Souza^b,
Fábio de Ávila Rodrigues^b, Alberto José Delgado dos Reis^c, Paula Peixoto Assemany^d,
Maria Lúcia Calijuri^a

^a Department of Civil Engineering, Federal University of Vicosa (Universidade Federal de Vicosa/UFV), Av. Peter Henry Rolfs, s/n, Campus Universitário, Vicosa, Minas Gerais, 36570-900, Brazil

^b Chemical Department, Federal University of Viçosa (Universidade Federal de Viçosa), Viçosa, MG, Brazil

^c Bioenergy and Biorefineries Unit, National Laboratory of Energy and Geology (UBB/LNEG), Lisbon, Portugal

^d Federal University of Lavras, Environmental Engineering Department, Campus Universitário, Lavras, Minas Gerais, Brazil



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ABSTRACT

Microalgae-based wastewater treatment is increasingly viewed as a cleaner production strategy, combining nutrient removal and biomass generation for high-value applications. However, productivity constraints remain a critical barrier to broader implementation. This study examines the viability of integrating light-emitting diodes (LEDs) into outdoor bubble column reactors for domestic wastewater treatment and biomass production, focusing on environmental impacts and techno-economic performance. Three lighting regimes—natural light only (control), 12-h LED cycles, and 24-h LED cycles—were experimentally evaluated and scaled up using Aspen Plus® simulation. Life cycle assessments (LCA) were conducted to quantify environmental impacts (ReCiPe, 2016 method), and a detailed techno-economic analysis determined minimum biomass selling prices. Compared to the control, LED-assisted systems increased biomass yields by 24–34 %, yet capital and operational costs offset productivity gains. Under grid electricity, minimum selling prices considering capital and operational costs ranged from 80.76 to 91.37 USD/kg for LED systems versus 68.85 USD/kg for the control. Photovoltaic (PV) integration reduced operational costs by up to 16.89 %, but LED scenarios remained more expensive. LCA findings highlighted substantially higher environmental impacts (78–149 times) for LED systems, partly alleviated by PV-powered operations. Sensitivity analysis identified nutrient availability, process scale, and reactor costs as pivotal factors influencing the feasibility of LED-enhanced wastewater treatment. Overall, while LED technology offers notable productivity benefits, its economic and environmental trade-offs underscore the need for integrated approaches—ranging from material innovations to policy incentives—to achieve truly sustainable wastewater-based microalgal production.

1. Introduction

Microalgal biotechnology has emerged as a promising alternative to conventional wastewater treatment, offering high pollutant removal efficiency, carbon capture, and the production of valuable metabolites. This integration of wastewater treatment with resource recovery provides a sustainable framework for waste management (Chen et al., 2023; Pereira et al., 2024). Nevertheless, low biomass yields, and high production costs limit broader implementation (Rajesh Banu et al., 2020).

Key strategy to address these challenges in microalgae cultivation involves leveraging the benefits of light-emitting diodes (LEDs). Schulze et al. (2014) demonstrated that LED quality significantly influences microalgal growth and biochemical profiles, while LEDs also offer spectral flexibility, energy efficiency, and durability (Ievina and Romagnoli, 2025). For instance, González-Camejo et al. (2019) reported a significant increase in biomass production—from 333 ± 86 mg/L to 538 ± 101 mg/L (in Volatile Suspended Solids)—by cultivating a mixed algae-bacteria consortium in outdoor flat-panel reactors equipped with

* Corresponding author.

E-mail addresses: iarabmagalhaes@yahoo.com.br, iara.barbosa@ufv.br (I.B. Magalhães).

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