RESEARCH ARTICLE

Microalgae-Based Wastewater Treatment Coupled with Biofuel Production: Techno-Economic Assessment

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Abstract: Integrating microalgae cultivation with municipal wastewater treatment enables simultaneous nutrient removal, CO_2 fixation, and biofuel feedstock production, but commercial viability depends on cultivation system design and downstream processing costs. We conduct a comprehensive techno-economic assessment (TEA) of high-rate algal pond (HRAP) and photobioreactor (PBR) systems treating 10 MLD of secondary effluent at four climate zones, coupled with hydrothermal liquefaction (HTL) for biocrude production. The HRAP-HTL pathway achieves wastewater treatment costs of \$0.18/m³ (vs. \$0.32/m³ for conventional activated sludge) while producing 42 tonnes/year of biocrude per MLD treated. PBR systems yield 2.8× higher biomass productivity but require 3.5× capital investment. Sensitivity analysis identifies biomass productivity, biocrude yield, and carbon credit pricing (\$50-80/tonne CO_2) as the dominant parameters affecting net present value (NPV), with breakeven achieved at \$72/tonne CO_2 credit price for HRAP systems in subtropical climates.

1. Introduction

Global wastewater generation exceeds 380 billion m³ annually, and conventional activated sludge treatment consumes 0.3-0.6 kWh/m³ while producing sludge requiring costly disposal. Microalgae offer an alternative biological treatment pathway that captures nutrients (N, P) for biomass growth while fixing CO_2 through photosynthesis. The resulting biomass can be converted to biofuels via transesterification (biodiesel), hydrothermal liquefaction (biocrude), or anaerobic digestion (biogas), creating a circular bioeconomy model that offsets treatment costs through product revenue.

2. Process Design and TEA Methodology

We modeled two cultivation configurations — open HRAPs (0.3 m depth, 5-day HRT) and closed flat-panel PBRs (0.05 m light path, continuous operation) — integrated with municipal WWTP secondary clarifier effluent (TN: 25 mg/L, TP: 4 mg/L). Downstream processing includes centrifugation (10% solids), HTL at 300°C/15 MPa (biocrude yield 38 wt%), and biocrude upgrading via hydrotreating. TEA uses a 20-year project horizon, 8% discount rate, and equipment costs from vendor quotes (2025-2026).

Table 1. Key performance and economic metrics for microalgae-wastewater systems (10 MLD capacity, subtropical climate)

System	Biomass Productivity (g/m²/d)	N Removal (%)	P Removal (%)	Biocrude (t/yr)	NPV ($M)	IRR (%)
HRAP + HTL	18.5	82	91	420	2.8	11.2
PBR + HTL	52.0	95	98	1,180	-1.5	4.8
HRAP + Biodiesel	18.5	82	91	285*	-3.2	2.1
Activated Sludge (ref.)	—	85	88	—	—	—

3. Results

HRAP systems outperform PBRs on an NPV basis in all four climate zones due to lower capital intensity, despite 2.8× lower biomass productivity. Figure 1 shows the tornado sensitivity chart for HRAP-HTL NPV, with carbon credit price and biomass productivity as the two most influential variables. Figure 2 compares treatment cost per m³ across climate zones, demonstrating that subtropical and tropical locations achieve the lowest costs due to extended cultivation seasons.

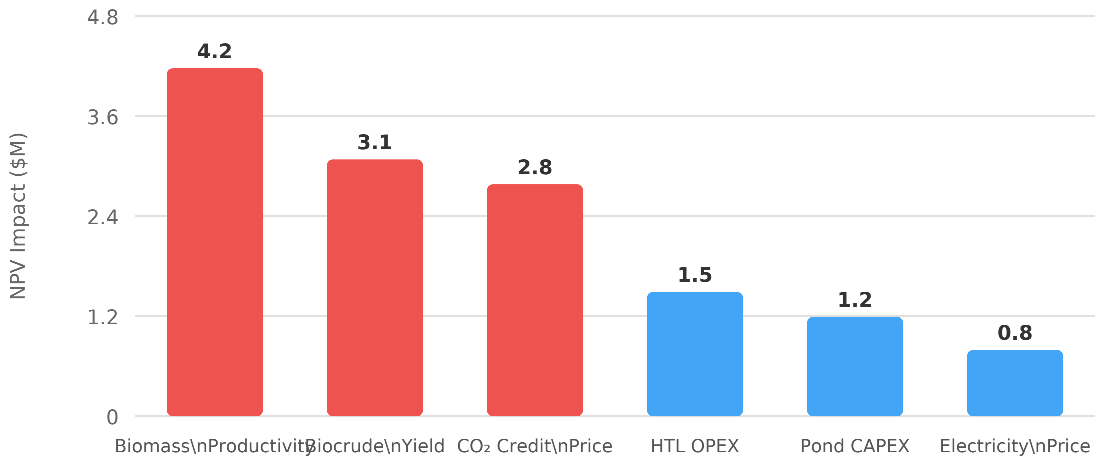

Figure 1. Sensitivity of HRAP-HTL project NPV to key economic and technical parameters (base case: subtropical, 10 MLD)

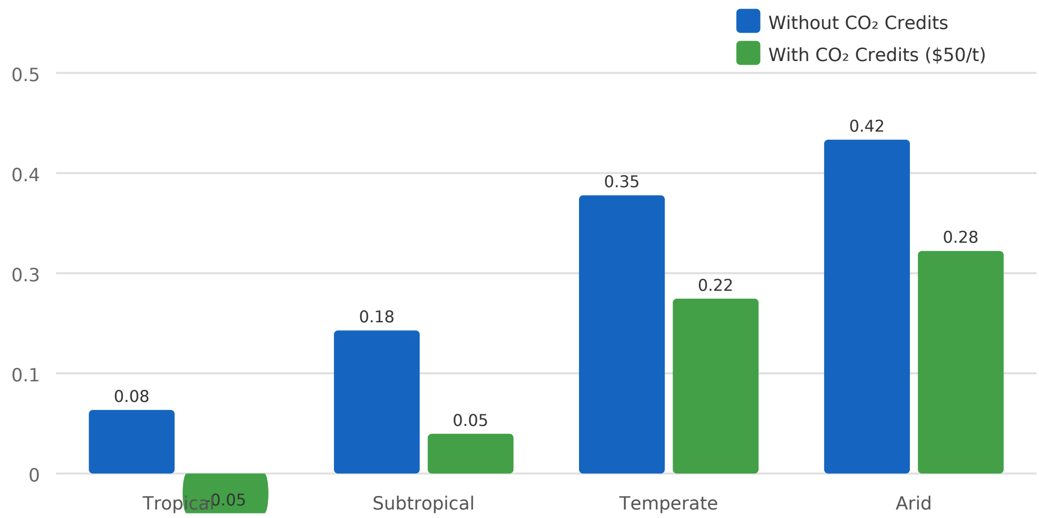

Figure 2. Net wastewater treatment cost ($/m³) for HRAP-HTL systems across four climate zones with and without carbon credits

4. Conclusions

Microalgae-based wastewater treatment coupled with HTL biofuel production is economically viable under current technology and policy conditions in subtropical and tropical climates, achieving negative net treatment costs when carbon credits exceed $50/tonne CO_2. Open pond systems provide the most favorable economics for municipal-scale deployment, while PBR systems may be justified where land availability is constrained and nutrient removal standards are stringent. Policy support through carbon pricing, renewable fuel mandates, and wastewater treatment subsidies will be critical to accelerate commercial deployment.

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