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Optimization of Microalgae-Based Biofuel Production: Process Parameters, Yield Maximization, and Economic Viability

Aamir Rahman[1*], Suraj Patil[2*], Vijay Deshmukh[3*]

[1]Department of Chemical Engineering, Dr. Harisingh Gour Vishwavidyalaya , Sagar, India
[2]Department of Biological Engineering, Central University of Jaharkhand, Ranchi, India
[3]Department of Environmental Engineering, Shivaji University, Dehradun, India
[*]Email: aamir.r@dhgv.ac.in, suraj.ce@cujh.ac.in, vijay.d@sju.ac.in

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Abstract: The escalating demand for sustainable energy sources has intensified interest in microalgae-based biofuels due to their high lipid productivity, rapid growth rates, and ability to utilize non-arable land and wastewater resources. Despite these advantages, large-scale commercialization remains constrained by suboptimal yields and high production costs. This study investigates the optimization of microalgae-based biofuel production through systematic evaluation of key process parameters, including nutrient concentration, light intensity, temperature, and carbon dioxide supply. Laboratory-scale cultivation experiments were conducted using Chlorella vulgaris in controlled photobioreactors to assess biomass productivity and lipid accumulation under varying operational conditions. Lipid extraction and transesterification processes were employed to determine biodiesel yield and fuel quality. In addition, a preliminary techno-economic analysis was performed to evaluate production feasibility at scale. Results demonstrate that optimized growth conditions significantly enhance lipid productivity while reducing energy input per unit biomass. The study concludes that integrated process optimization and cost-reduction strategies are essential for improving the economic viability of microalgae-derived biofuels.

Keywords: Microalgae Biofuel, Lipid Productivity, Bioprocess Optimization, Renewable Energy, Techno-Economic Analysis

1. Introduction

Global dependence on fossil fuels has resulted in resource depletion, greenhouse gas emissions, and environmental degradation. Renewable biofuels have emerged as viable alternatives; however, first-generation biofuels derived from food crops raise concerns regarding food security and land use. Microalgae have attracted significant attention as third-generation biofuel feedstocks due to their superior photosynthetic efficiency, high lipid content, and ability to grow in diverse environments [1]. Despite extensive research, commercialization of microalgae-based biofuels remains limited by low energy return on investment and high operational costs. Optimizing cultivation and processing parameters is therefore critical to enhancing productivity and improving economic feasibility. This study aims to experimentally evaluate key growth parameters influencing biomass and lipid yield and to assess the techno-economic implications of optimized production.

2. Microalgae Selection and Cultivation Strategy

Chlorella vulgaris was selected for this study due to its robust growth, high lipid accumulation potential, and adaptability to controlled cultivation systems. The microalgae were cultivated in closed photobioreactors to minimize contamination and allow precise control over environmental conditions.

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Growth media composition was modified to evaluate the effects of nitrogen limitation on lipid accumulation. Carbon dioxide supplementation was provided to enhance photosynthetic activity, while continuous mixing ensured uniform light exposure and nutrient distribution [2].

3. Experimental Methodology

Cultivation experiments were conducted under varying light intensities ranging from 100 to 400 μmol photons $m^{-2} s^{-1}$, temperatures between 20°C and 35°C, and nitrogen concentrations adjusted to induce lipid accumulation. Biomass concentration was measured gravimetrically, while growth kinetics were analyzed using specific growth rate calculations. Lipid extraction was performed using solvent-based methods, followed by transesterification to produce biodiesel. Fuel properties such as viscosity, density, and calorific value were evaluated according to ASTM standards [3].

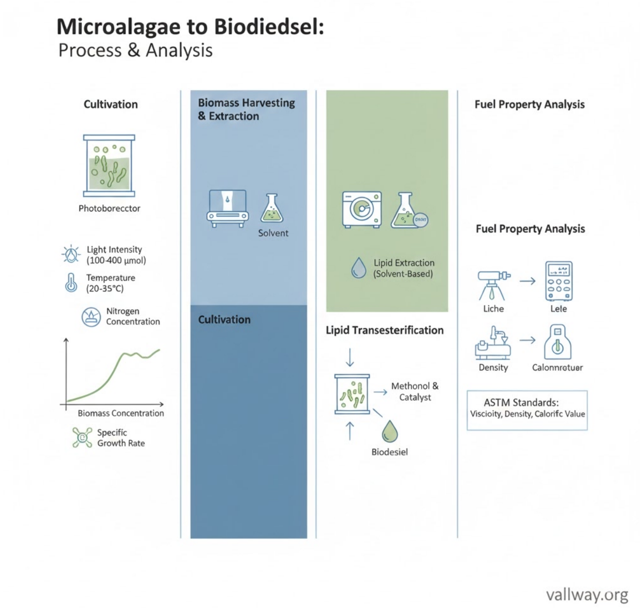

Fig. 1

4. Influence of Process Parameters on Biomass and Lipid Yield

Results indicate that moderate nitrogen limitation significantly enhances lipid accumulation while slightly reducing biomass growth rate. Optimal temperature and light intensity conditions resulted in maximum lipid productivity rather than maximum biomass concentration, emphasizing the importance of yield-based optimization. Carbon dioxide enrichment improved biomass productivity by enhancing carbon fixation efficiency. However, excessive CO_2 supply resulted in diminishing returns due to pH imbalance and metabolic stress.

5. Biodiesel Yield and Quality Assessment

Extracted lipids were successfully converted into biodiesel with conversion efficiencies exceeding 90%. Fuel property analysis demonstrated compliance with international biodiesel standards, confirming suitability for engine applications. Fatty acid methyl ester profiles revealed a favorable composition dominated by C16 and C18 chains, contributing to desirable combustion characteristics and oxidative stability [4].

6. Techno-Economic Analysis

A preliminary techno-economic assessment was conducted to estimate production costs under optimized conditions. Major cost contributors included photobioreactor capital investment, energy input for mixing and lighting, and downstream processing expenses. Optimization of cultivation parameters reduced energy consumption per unit biomass, improving overall process economics. Integration with wastewater treatment and utilization of flue gas CO_2 were identified as potential strategies for further cost reduction [5].

7. Challenges and Future Research Directions

While optimization improves productivity, scalability remains a major challenge. Future research should focus on strain improvement, low-energy harvesting techniques, and hybrid cultivation systems combining open ponds and closed reactors. Policy support and carbon pricing mechanisms may further enhance the competitiveness of microalgae-based biofuels.

8. Conclusion

This study demonstrates that systematic optimization of cultivation parameters significantly enhances microalgae biomass and lipid productivity while improving economic feasibility. Microalgae-based biofuels represent a promising renewable energy pathway, provided that technological and economic challenges are addressed through integrated engineering approaches.

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