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Bio-oil from hydrothermal liquefaction of microalgae cultivated in wastewater: An economic and life cycle approach

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A B S T R A C T

Although microalgae are a promising sustainable biofuel feedstock, their energy-intensive production and most environmental assessments rarely achieve the desired trade-off between productivity and sustainability. In this context, this study aims to evaluate the economic and environmental feasibility of producing bio-oil via hydrothermal liquefaction (HTL) of wastewater-grown microalgae at an industrial scale. Four scenarios varied production scale and steam source: sugarcane bagasse (SCB) in SC1 and SC3, liquefied petroleum gas (LPG) in SC2 and SC4. Each scenario processed microalgae at 300 °C for 30 min. Smaller-scale feedstock (1332.9 kg/h) in SC1 and SC2 produced 34.6 kg/h of bio-oil, while the larger feedstock (85,554.4 kg/h) in SC3 and SC4 yielded 2222.2 kg/h. Microalgae biomass cultivation costs dominated overall expenses (56–75 %). Economic analyses indicated minimum selling prices of 3.82–8.52 USD/kg, exceeding the average literature figure of 1.57 USD/kg. Life Cycle Assessment (LCA) showed SCB reduced fossil resource depletion by 14.97 % compared to LPG but increased emissions of nitrogen oxides, particulates, and toxic compounds, which are manageable via selective catalytic reduction and flue gas desulphurization. Cyclohexane as a solvent elevated human carcinogenic toxicity, greener alternatives could reduce toxicity but may cost more, requiring further cost analysis. Advancing this biorefinery route requires optimization of cultivation and processing costs, adoption of environmentally benign solvents, and implementation of emission control strategies to enable economically feasible and environmentally sustainable bio-oil production.

1. Introduction

The escalating global demand for sustainable energy and the urgent need to mitigate climate change have intensified research into renewable alternatives to fossil fuels (IEA, 2023). Projections indicate that by 2050, the world's energy demand will increase by 50 %, highlighting the necessity to develop clean and efficient energy sources (EIA, 2023). Among various renewable options, microalgae have emerged as a promising feedstock for biofuel production due to their rapid growth rates and high biomass yield, up to 30 times greater per area than traditional terrestrial crops (Parray et al., 2024).

In addition to their productivity, microalgae contribute to climate change mitigation by capturing atmospheric carbon dioxide (CO_2) at an estimated rate of about 1.8 kg of CO_2 per kilogram of dry biomass produced (Cheah et al., 2015). Moreover, cultivating microalgae in wastewater presents an integrated approach that combines effluent treatment with the production of energy-rich biomass (Calijuri et al., 2022). Studies have demonstrated that microalgal cultivation can remove up to 80–100 % of nutrients such as nitrogen (N) and phosphorus (P) from wastewater, thereby addressing environmental pollution while generating valuable biomass (Delgadillo-Mirquez et al., 2016). This dual functionality supports both environmental remediation and resource recovery, reinforcing the role of microalgae within circular economy frameworks.

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