



Comparison of algae cultivation methods for bioenergy production using a combined life cycle assessment and life cycle costing approach

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HIGHLIGHTS

- Environmental and economic performance of open ponds and photobioreactors are compared.
- Open ponds deliver better energy return on investment and greenhouse gas performances.
- Open ponds deliver higher profitability index.
- Market forces are key to improved financial outlook for open pond operations.

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ABSTRACT

Algae are an attractive energy source, but important questions still exist about the sustainability of this technology on a large scale. Two particularly important questions concern the method of cultivation and the type of algae to be used. This present study combines elements of life cycle analysis (LCA) and life cycle costing (LCC) to evaluate open pond (OP) systems and horizontal tubular photobioreactors (PBRs) for the cultivation of freshwater (FW) or brackish-to-saline water (BSW) algae. Based on the LCA, OPs have lower energy consumption and greenhouse gas emissions than PBRs; e.g., 32% less energy use for construction and operation. According to the LCC, all four systems are currently financially unattractive investments, though OPs are less so than PBRs. BSW species deliver better energy and GHG performance and higher profitability than FW species in both OPs and PBRs. Sensitivity analyses suggest that improvements in critical cultivation parameters (e.g., CO₂ utilization efficiency or algae lipid content), conversion parameters (e.g., anaerobic digestion efficiency), and market factors (e.g., costs of CO₂ and electricity, or sale prices for algae biodiesel) could alter these results.

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1. Introduction

Transportation consumes approximately 30% of the world's primary energy (US DOE, 2011), depleting petroleum resources and contributing to anthropogenic climate change (US DOE, 2011). Thus, there is significant interest in algal biofuels as possible alternatives to fossil fuels. This interest arises from several of algae's unique benefits vis-a-vis fuels derived from terrestrial plants: e.g., high productivity per unit area and high lipid content for direct conversion into liquid fuels (Benemann and Oswald, 1996; Chisti, 2007). Recent LCA work on hypothetical large-scale algae-to-energy systems suggests that cultivation impacts are perhaps the most environmentally burdensome components of the overall algae-to-fuel life cycle (Clarens et al., 2010; Stephenson

et al., 2010). For this reason, it is desirable to understand, compare, and optimize possible algae cultivation systems. Two particularly relevant questions concern: what growth configurations should be used and the type of algae.

Considerable progress regarding algae cultivation has already been made, especially as pertaining to open pond (OP) systems and horizontal tubular photobioreactors (PBRs), the leading contenders for large-scale algae cultivation; however, there is no consensus about which cultivation method is preferable because both systems possess seeming advantages and disadvantages (Stephens et al., 2010). OP systems are less expensive and require less energy to construct and operate than PBRs (Benemann and Oswald, 1996; Fischer et al., 2011). They are also easily deployed and scaled up (Davis et al., 2011), but because they are not enclosed, they are susceptible to contamination and evaporation. PBR systems are more complex and thus more expensive to build and operate than OP systems (Molina-Grima et al., 2003; Chisti, 2007), but they provide

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